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Developing an inventory model for the Korean Air Force repairable item inventory.

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DEVELOPING AN INVENTORY MODEL FOR THE KOREAN AIR FORCE REPAIRABLE ITEM INVENTORY

by

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The Korean Air Force has determined that repairables management is one of the areas in which attention could be expected to lead to substantial improvement in the efficient management of defense resources and in maintaining an adequate level of force effectiveness. This thesis reviews various inventory models for the management of repairable items and develops an inventory model for the Korean Air Force. It discusses the characteristics of each model, and, identifies and explains the differences in each model with respect to assumptions, objectives, constraints, and optimization methods. Also this research evaluates the proposed model using sample data sets.

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Developing an Inventory Model for the Korean Air Force Repairable Item Inventory

by

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ABSTRACT

The Korean Air Force has determined that repairables management is one of the areas in which attention could be expected to lead to substantial improvement in the efficient management of defense resources and in maintaining an adequate level of force effectiveness. This thesis reviews various inventory models for the management of repairable items and develops an inventory model for the Korean Air Force. It discusses the characteristics of each model, and, identifies and explains the differences in each model with respect to assumptions, objectives, constraints, and optimization methods. Also this research evaluates the proposed model using sample data sets.

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I. INTRODUCTION

A. BACKGROUND

The objective of the Korean Air Force supply system is to ensure the desired level of operational availability for its population of repairable equipment and maintain sufficient stock levels for replacement components and repair parts to support the maintenance of existing weapon systems and equipment. Also, the Korean Air Force supply system is responsible for stocking a number of items which are failure prone and have been designated as repairable. Because of engineering and economic considerations, attempts are made by Korean Air Force repair activities to restore these items to serviceable condition whenever they fail.

The repairable inventory system differs from that of the consumable inventory system in two ways. First, the repairable system contains two distinct inventories, one of which has items that are in a Ready-For-Issue (RFI) state and another which has items that are in a Non-Ready-For-Issue (NRFI) state. The first inventory contains items which are usable and the second contains items that must be repaired before they can be used. Second, the RFI inventory is made up of a mixture of new items and items that have been used, failed, repaired, and are ready to be used again. This is one reason why repairable inventory management is a complicated process. [Ref. 1: p. 2]

The Korean Air Force Logistics Command (KAFLC) tries to determine an appropriate stock level for repairables based on a primitive mathematical model. This model estimates stock levels using rules of thumb based on expert opinion. However, it is very difficult to determine an optimal stock level for a repairable without using a more sophisticated inventory management model. The result of the lack of such a model is that the Korean Air Force supply system tends to maintain relatively high stock levels for repairable components. Although, repairable items account for only a small percentage of the quantity of items stocked throughout the Korean Air Force, they account for a large portion of dollars invested in inventory. The characteristics of high cost and high essentiality that these items typically possess make efficient inventory control difficult and extremely critical.

Historically, most inventory models have been developed for the private sector where the profit motive is important. Such models consider the various average annual variable costs associated with managing inventories and strive to minimize the sum of these costs. The typical relevant costs in most inventory models are ordering cost, holding cost and stockout cost. Certainly, these cost parameters are very important in the common concept of inventory management. [Ref. 2: p. 1]

However, in military supply systems, it is hard to estimate the costs associated with stockouts. In addition, the military supply system is not interested in profit maximization or cost minimization. Instead, such an organization is usually interested in maximizing the ability of its forces to respond to any threat. An objective which maximizes some measure of readiness with given resources is therefore appropriate.

B. PURPOSE OF RESEARCH

The effective accomplishment of each flying mission is dependent upon having sufficient numbers of aircraft ready to fly and to perform at their fullest capability. To support this goal, the Korean Air Force emphasizes an extensive system of supply and maintenance capabilities. The Korean Air Force also tries to maximize the availability of aircraft by quickly identifying malfunctioning parts, removing them, and rapidly installing replacements which have been positioned at the base supply department.

The purpose of this thesis is the development of an inventory model for the management of repairable items at the wholesale level by the Korean Air Force Logistics Command (KAFLC). This will be accomplished by the analysis of various repairable inventory management models which have been developed and applied to the management of inventories of repairable items in the United States military. And also, a numerical analysis will be accomplished based on a proposed model. Finally the inventory system parameters, and management concept will be studied.

C. PREVIEW

Chapter II of this thesis presents an overview of the current Korean Air Force Logistics Command (KAFLC) repairable items management process. This overview will explain the organization of the Korean Air Force Logistics Command, describe the present general methodology used for repairable items management and the current overall approach to the problem.

Chapter III gives a detailed description of the specific mathematical inventory models in use today for the management of repairables. Some explanation of their mathematical approach in solving the inventory problem is given.

In Chapter IV, the development of a model for the Korean Air Force repairables inventory management system is described. Model formulation and solution techniques are provided.

Chapter V will show numerical results from a computer program for comparing the proposed model and describe major components based on the findings in Chapters III and IV.

Finally, Chapter VI contains a summary and recommendations for future study based on the proposed repairables inventory management model.

II. REPAIRABLES AND THE KOREAN AIR FORCE LOGISTICS SYSTEM

A. INTRODUCTION

The Korean Air Force didn't use any kind of repairables inventory management model until the late 1960's. In the beginning of the 1970's, the first inventory management concept was introduced by the U.S Air Force. The economic inventory management model was used during this period.

The model adopted in the 1970's has been revised systematically several times since its adoption by the Korean Air Force. However, the usefulness of this inventory model has decreased as the weapon systems used in the Korean Air Force have become more sophisticated, and the overall size of the Korean Air Force has increased. The annual budget for repairables takes approximately 60-70 percent of the total annual stock fund budget of the Korean Air Force, however the essentiality of high quality repairables inventory management was not realized. [Ref. 1: p. 1]

In this chapter, the Korean Air Force Logistics system will be described. The chapter specifically deals with repairables management, organization, system parameters, and mathematical models related to repairable item management. This chapter will provide the basis for the analysis and suggested improvements to the Korean Air Force repairables inventory management system which will be described later.

B. THE KOREAN AIR FORCE LOGISTICS COMMAND ORGANIZATION

The Korean Air Force Logistics Command (KAFLC) is responsible for managing the allocation of the logistics resources to support maximum weapon system operational availability. It functions as an intermediate echelon command among the tactical units of the Korean Air Force under the policies and planning of Air Force Headquarters. Figure 1 shows the organization of the KAFLC. The following paragraphs will explain the basic missions and responsibilities of the six major divisions of the command.

The DMM (Directorate of Materials Management) is the focal point of material management for the Korean Air Force. It procures all materials according to its estimates of requirements, distributes the material to all of the tactical units and the supporting units under the policies of the KAFLC. Thus, the DMM is the equivalent of a wholesale level Inventory Control Point (ICP). The DMM manages approximately 210,000 items which are allocated among the hundreds of item managers. To manage

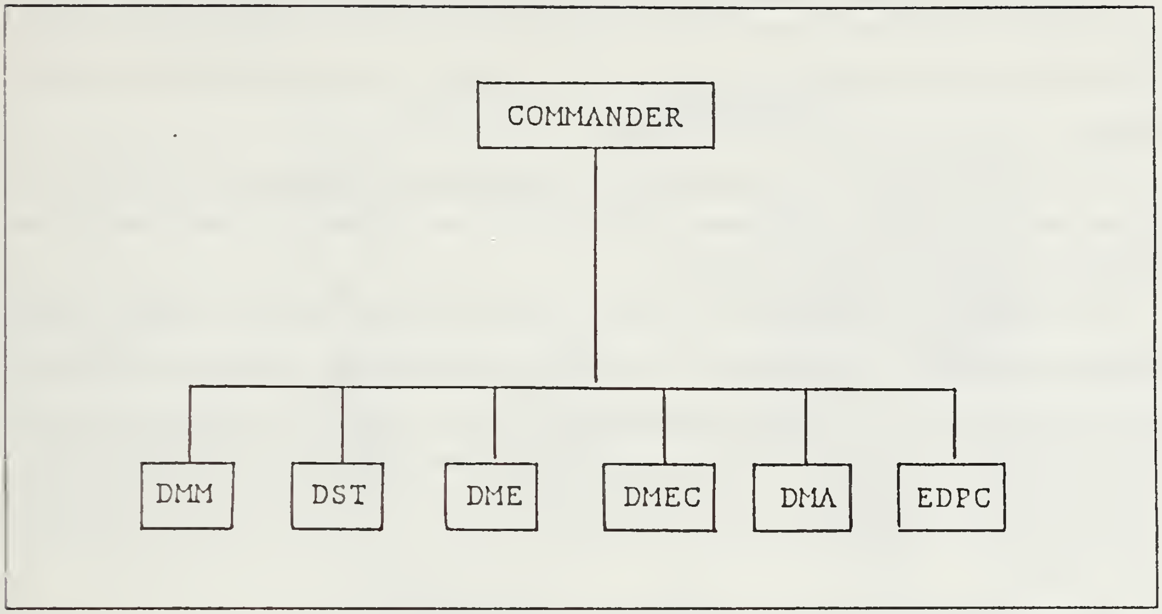

Figure 1. The Organization of the Korean Air Force Logistics Command

effectively, DMM relies heavily on the Electronic Data Processing Center's (EDPC) computer services to access historical transaction data, compute demand forecasts, current asset data, etc.

The DST (Depot of Storage and Transportation) is the centralized warehouse for the Korean Air Force where all procured and repaired materials, including consumables, are stored. They control the physical inventory of the items needed by the ultimate user. The DST also deals with the disposal of salvage, scrap, excess and obsolete material. The other important role of the DST is transporting all materials to arrive at the tactical unit when required.

The DME (Depot of Maintenance and Equipment) is the in-house depot level maintenance organization for the Korean Air Force. The primary task of the DME is the overhaul of aircraft on a scheduled basis (preventive maintenance). It performs the maintenance of aviation end items which are beyond the capabilities of the the intermediate and organizational maintenance level facilities. These items would be the major end items of an aircraft such as the engine, fuselage, gearbox and the direct ground support equipment for the operation of the aircraft.

The DMEC (Depot of Maintenance, Electronics and Communication) performs the maintenance of radar equipment and its subassemblies, ground communication equipment and weather forecasting equipment. The DMEC also performs preventive maintenance.

The DMA (Depot of Maintenance and Ammunition) performs the maintenance of the precision measurement equipment (PME), airborne equipment and armament of the aircraft, such as laser guidance system.

The EDPC (Electronic Data Processing Center) provides logistics software development and support, establishes job processsing standardization, collection of data related to preventive and corrective maintenance, provides analysis and guidance for each of the other major divisions. The major objective of the EDPC is to assist each division in performing their specialized logistics missions within the Korean Air Force Logistics Command.

C. REPAIRABLE ITEMS MANAGEMENT SYSTEM

1. The General System Overview

In the Korean Air Force an item of supply is designated as a repairable if it can be repaired faster and less expensively than it can be procured. Weapon systems installed in aircraft have become increasingly sophisticated and complex. Hence, many weapon systems are made up of a number of subsystems which in turn are comprised of several repairable modules. Often the complexity of these individual modules are such that the personnel and equipment are not available at the end user level to repair failed units. Consequently, these modules are designated as repairables and failed units are returned to designated repair activities for repair. Therefore, repairables management has become an essential part of the Korean Air Force supply system in terms of decision making. Figure 2 shows the current Korean Air Force repairables management cycle.

The Korean Air Force has two kinds of maintenance operations for repairables, the base maintenance (organizational and intermediate level) and the depot level maintenance (DME, DMEC, DMA). It should be noted that not all depot level repairables are repaired at the Korean Air Force facilities. Because of the complexity, some repairs are done by the USAF under Foreign Military Sales (FMS) using commercial contractors. As depicted in Figure 2, three kinds of repairables flows are shown. The first is the flow of carcasses to base level maintenance. The second is the flow of carcasses to depot level maintenance. The third level is the flow of carcasses from the DST to the USAF (the activities that coordinate with USAFLC for repair and procurement follow FMS

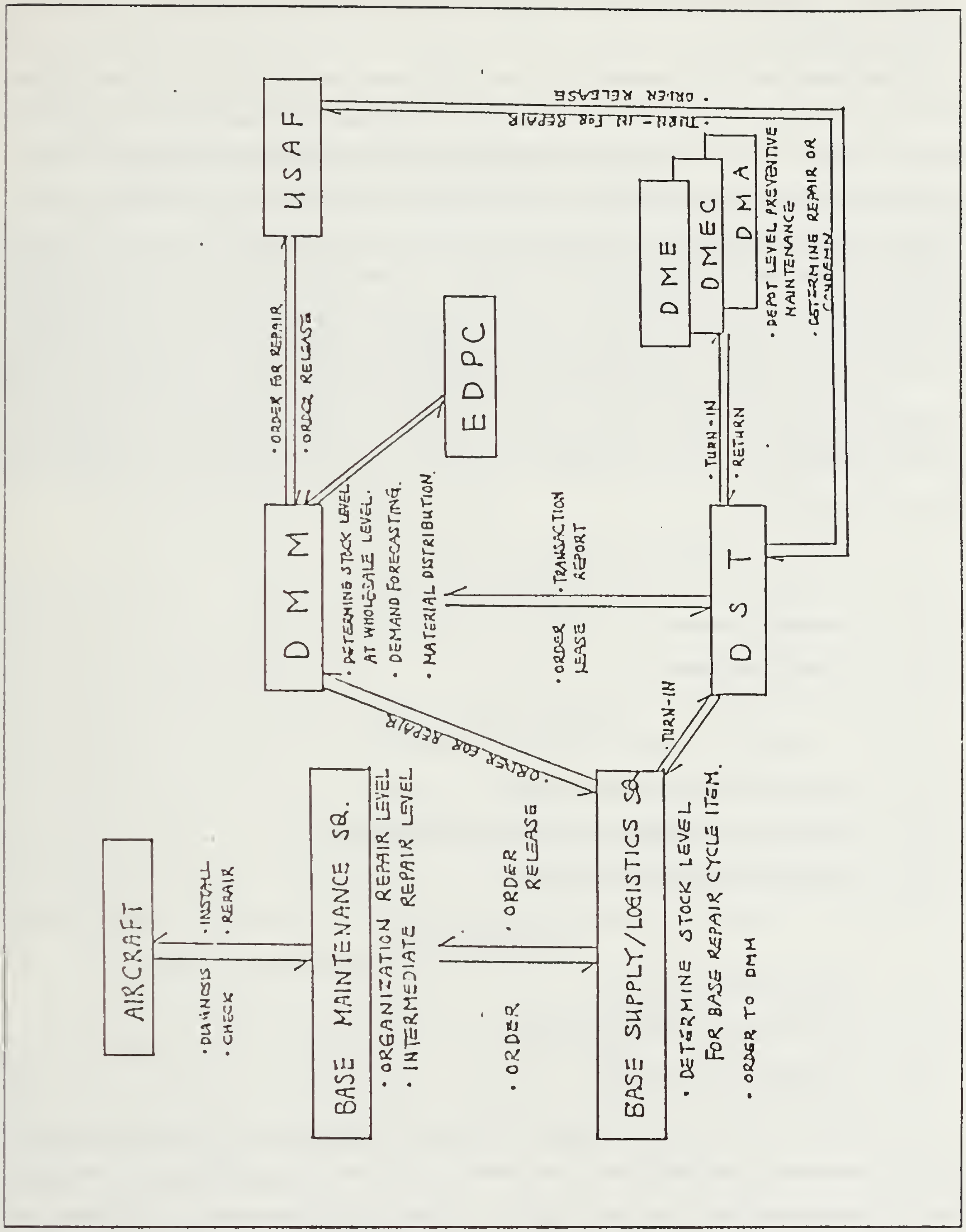

Figure 2. The Korean Air Force Repairable Management Cycle

procedures). Note that the third flow implies the exchange of a carcass for a new item from the USAFLC.

When a failure of a system or subsystem occurs, the equipment is inspected to determine the cause of the failure. After isolation of the failure to a component or major assembly, further inspection is done to determine if base level repair is possible. In case of the failure of a major end item, an RFI (Ready-for-Issue) item from the base supply is used to replace the failed item and the aircraft returns to operational status. This insures the operational availability of an aircraft. If possible, the failed item is repaired by the Base Maintenance Squadron (organization or intermediate level of repair). After such a repair, the item is released to the Base Supply Squadron in serviceable condition.

For the determination of the maintenance level, the Korean Air Force has a special code assigned to each replaceable component of a major end item. Thus, the level of maintenance for each component is predetermined by this code. The code is as follows. [Ref. 3: p. 7]

First code position

X	expendable item
N	repairable item

Second code position

D	depot level maintenance item
F	field level maintenance item (intermediate)
B	base level maintenance item

Third code position

1	depot level maintenance
2	intermediate level maintenance
3	no maintenance action

After the Base Supply Squadron has issued a serviceable item from its stocks and when base level maintenance has been determined to be impossible, the Base Supply Squadron sends the failed item to the DST. Of course, all these actions are reported to and directed centrally by the DMM. The failed items from each base are placed in the DST facility and await repair. These carcasses are turned over to the depot maintenance facility (DME, DMEC, DMA) in batches under the approval of the DMM. In other words, all carcasses from each base are stocked in the DST facility during the quarter. At the end of each quarter, all carcasses are sent to the depot maintenance facility (DME, DMEC, DMA). However, at this time, item managers of the DMM consider the capacity limit of the depot maintenance facility.[1]

2. Operating Characteristics of Repairables Management

As mentioned earlier, there are several depot maintenance organizations in the Korean Air Force. However, their concept of operation and relations with the DMM are identical for the DME, DMEC and DMA. So, only the operation of DME will be covered here. The maintenance organization of the Korean Air Force is restricted in terms of its capacity to process incoming repairs and in terms of the level of technology to deal with the repair of complex systems. Thus, the MRS (Material Repair Schedule) and MRRL (Material Repair Return List) are established to manage these restrictions.

a. Material Repair Schedule (MRS)

The MRS is the repair schedule for the depot maintenance facility. It describes the type and quantity of repairable material which can be repaired during the next fiscal year by repair depots operated by the Korean Air Force. In September of the fiscal year, all item managers estimate the demand for each repairable item for the next year, and the total repair quantity, based on data from the last several years. The integrated results for each item are provided to the DME, DMEC, and DMA. Then, the DME, DMEC and DMA set up their repair schedules after discussion and coordination with DMM. The forecasted maintenance requirements which are not covered by the MRS are turned over to the MRRL. The repair quantity for the MRS is set up on a quarterly basis and carcasses are issued from the DST based on capacity of the DME.

b. Material Repair Return List (MRRL)

This is the list of repairables for which the Korean Air Force does not have depot level maintenance capability, either due to technology or capacity restrictions. In the case of an MRRL repair, the DST sends the carcasses to a USAF depot facility. Upon the receipt of the carcass from the Korean Air Force, the USAF returns a serviceable unit to the DST. Serviceable units from both the USAF and Korean Air Force depot facility are integrated at the DST to make up the serviceable stocks which are available to support for the tactical unit.

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1 This capacity limit established based on the MRS, see paragraph 2.a. above.

c. *The Measure of Performance*

The Korean Air Force supply system (wholesale level) uses two measures of performance. The first one is fill rate. It is also used by the base level supply system. The second measure is supply response time. It measures the length of time elasped for base backorders to be satisfied by the stock from the DST. In other words, it is the length of time from the placement of an order with the DMM to the receipt of the ordered item. Notice that the DMM uses this more as a priority rule for issuing the stock than as a general measure of performance for management of the repairable items. Currently, the Korean Air Force assumes that any backorders for spares result in an aircraft being "not operationally ready because of supply" (NORS). Thus, the Korean Air Force has developed codes which indicate the NORS condition. Each code provides the maximum supply response time requirement to fill backorders. Table 1 summarizes the supply response time requirements for each demand with priority and Table 2 describes the meaning of each NORS code. [Ref. 4: p. 81]

Table 1. SUPPLY RESPONSE TIME REQUIREMENTS

Priority	Type of order	Response time (day)	Circumstances
03	Express	3	G, K NORS
06	Semi-express	14	A, F NORS
13	Routine	30	Routine

Table 2. DESCRIPTION OF NORS CODE

NORS Code	Description
G	Aircraft is in a Totally inoperational condition
K	Radar malfunctioning
F	Operational, incapable of mission
A	NORS is anticipated

D. MATHEMATICAL BACKGROUND OF REPAIRABLES MANAGEMENT

1. DDR (Daily Demand Rate)

This is the average number of demands per day and it is computed following formula:[2]

$$DDR = \sum_{i=1}^{365} \frac{D_i}{365}$$

where:

D_i = demand on the ith day of the year

2. DRP (Depot Repair Percent)

It is computed in the following manner for each repairable item from the last three years of historical data:

$$DRP = \frac{RTS}{RTS + NRTS + COND} \times 100$$

where:

RTS = repair this station

NRTS = non-repair this station

COND = condemned

RTS refers to the number of units repaired at the Korean Air Force depot. Conversely NRTS refers to the number of units repaired by the commercial contractors or by the USAF under FMS policies. Thus, NDRP (Non-Depot Repair Percentage) is the complement of DRP.

3. RCT (Repair Cycle Time)

The Korean Air Force has two kinds of repair cycle time. The one is the repair cycle time associated with base maintenance and the other is associated with the depot level maintenance. Usually RCT refers to the time allowed for the depot level maintenance only. This time allowance is the policy of the Korean Air Force. So, RCT is constrained[3] to be not less than 30 days and not more than 120 days.

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2 This is computed by the end of year. The time period of this computation starts from the first day of the year to the end of the year.

3 This is the policy of the Korean Air Force, not a value which is computed from actual observations which are recorded in the inventory management database.

4. **RCQ (Repair Cycle Quantity)**

This refers to the quantity of the repairable item which must be stocked to meet demands during the repair cycle time. RCQ is applied to MRS items only and computed by the following formula:

$$RCQ = DDR \times DRP \times RCT$$

where:

DDR = daily demand rate

DRP = depot repair percentage

RCT = repair cycle time (days)

5. **OLQ (Operational Level Quantity)**

This is the stockage quantity which is required to cover forecasted demand during the time an MRRL item is in the hands of the USAF for repair. OLQ is related to MRRL as RCQ is to an MRS item. The formula for OLQ is as follow:

$$OLQ = DDR \times 60 \text{ day}$$

where:

DDR = daily demand rate

6. **OST (Order and Shipping Time)**

OST is defined as the time elasped from the initiation of a procurement or repair order, to the receipt of the order. In the case of a procurement, the Korean Air Force constrains the OST to be not less than 120 days and not greater than 365 days. For MRRL repairables, OST is constrained to be not less than 220 days and not greater than 465 days. In both cases, the upper and lower intervals are adopted to avoid an inventory stockout. The 100 days increment in the OST is due to the additional transportation time for MRRL items from Korea to the continental U.S.A.

7. **OSTQ (Order and Shipping Time Quantity)**

OSTQ refers to the quantity of repairable items needed to meet the demand during the order and shipping time. The formula for OSTQ is as follows:

for MRS items, $OSTQ = DDR \times NDRP \times OST$

for MRRL items, $OSTQ = DDR \times OST$

where:

DDR = daily demand rate

NDRP = non-depot repair percentage

OST = order and shipping time

8. SLQ (Safety Level Quantity)

This refers to the quantity of repairables stocked to meet demand during delays in shipping, delays in maintenance, or unexpected increases in demand. The formula for SLQ is as follows:

$$\text{for MRS items,} \quad SLQ = \sqrt{3 \times (RCQ + OSTQ)}$$

$$\text{for MRRL items,} \quad SLQ = \sqrt{3 \times OSTQ}$$

where:

RCQ = repair cycle quantity

OSTQ = order and shipping time quantity

9. RO (Requisition Objective)

Even with the assistance of the existing computer system, it is hard for the item managers to manage the more than 2,000 items (per item manager) that are assigned to them. Thus, the DMM designates items that have two or more requisitions per year as requisition objective items. The item managers will monitor these items more closely.

Currently, the DMM applies a periodic inventory review model which is based on a policy of reviewing and repairing at fixed regular intervals to bring inventory levels back up to the Requisition Objective (RO). Repair orders are placed at predetermined intervals[4] (the expected demand between intervals plus some allowance for the variability of demand must be considered).

The requisitioning objective consists of three terms. These are the order and shipping time quantity (OSTQ), the repair cycle quantity (RCQ) and safety level quantity (SLQ). The requisitioning objective is the sum of these components. In Figure 3, the repair order quantity is simply the difference between RO and the on hand inventory at time of review.

Since the system parameters such as OST, RCT, DDR, DRP and NDRP differ at each review period, the level of the RO may also be different at the time of each re-

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[4] This predetermined interval is the repair induction interval on the MRS. The current length of the interval is 2 months.

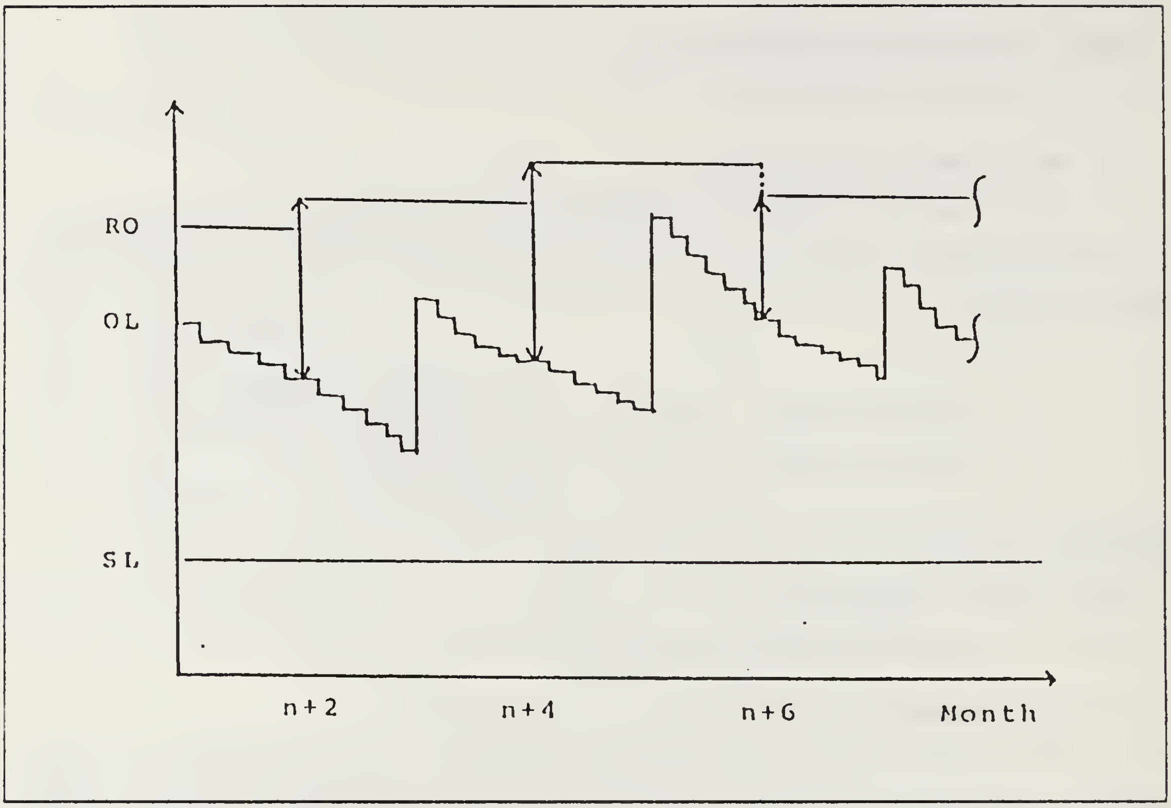

Figure 3. The Korean Air Force Repairables Inventory Periodic Review

view. Inventory reviews are usually done every 2 months. The formula for RO is shown below:

$$\text{for MRS items,} \quad RO = SLQ + RCQ + OSTQ$$

where:

$\mathrm{SLQ} = \sqrt{3 \times (\mathrm{RCQ} + \mathrm{OSTQ})}$

$\mathrm{RCQ} = \mathrm{DDR} \times \mathrm{DRP} \times \mathrm{RCT}$

$\mathrm{OSTQ} = \mathrm{DDR} \times \mathrm{NDRP} \times \mathrm{OST}$

$$\text{for MRRL items,} \quad RO = SLQ + OLQ + OSTQ$$

where:

$\mathrm{SLQ} = \sqrt{3 \times OSTQ}$

$\mathrm{OLQ} = \mathrm{DDR} \times 60 \text{ days}$

$\mathrm{OSTQ} = \mathrm{DDR} \times \mathrm{OST}$

10. History of RO Computation

This section shows the history of the RO computation formula. The Korean Air Force tries to determine optimal stock level for the repairables inventory management system. However, the results of changing the RO formulation without adequate consideration of the system parameters may result in excess stock for some items or stockouts for some items.

a. Before 1973

$$RO = OLQ + SLQ + OSTQ$$

where:

OLQ = DDR × 75

SLQ = DDR × 15

OSTQ = DDR × 30

b. Between 1973 and 1976

For MRS, $RO = DDR \times 120$

For MRRL, $RO = RCQ + SLQ + OSTQ$

where:

RCQ = DDR × 15

$SLQ = \sqrt{3 \times (RCQ + OSTQ)}$

OSTQ = DDR × 84

c. Between 1976 and 1979

$$RO = RCQ + SLQ + NCQ + OSTQ$$

where:

RCQ = DDR × DRP × RCT

SLQ = 3(RCQ + OSTQ + NCQ)

NCQ = DDR × NDRP × NCT

OSTQ = DDR × NDRP × OST

NCT = NRTS / Condemn Time[5]

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5 This (NCT) is a time spent for decisioning a condemnation among NRTS items.

d. Between 1979 and 1984

$$RO = RCQ + SLQ + OSTQ$$

where:

RCQ = DDR × DRP × RCT

SLQ = (DDR × NDRP × POST) + RCQ

OSTQ = DDR × NDRP × ROST

e. After 1984

$$\text{For MRS,} \quad RO = RCQ + SLQ + OSTQ$$

where:

RCQ = DDR × DRP × RCT

$\mathrm{SLQ} = \sqrt{3 \times (\mathrm{RCQ} + \mathrm{OSTQ})}$

OSTQ = DDR × NDRP × OST

$$\text{For MRRL,} \quad RO = OLQ + SLQ + OSTQ$$

where:

OLQ = DDR × 60

$\mathrm{SLQ} = \sqrt{3\,\mathrm{OSTQ}}$

OSTQ = DDR × OST

E. SUMMARY AND PROBLEM STATEMENT

As mentioned earlier, military inventory managers tend to want to increase their operational availability rather than minimize inventory costs. However, in the case of the Korean Air Force repairables management process, the mathematical model is insufficient to adequately model the stochastic characteristics of the inventory management problem. In the RO (Requisition Objective) computation it does not specify the wear-out rate or the regeneration rate, which are important parameters in dealing with repairables inventory management.

The DDR (Daily Demand Rate) computation is the mean of a stochastic process. However, the current inventory model treats demand as if it were deterministic. In the formula for SLQ (Safety Stock Quantity), they considered the stochastic nature of demand but the actual probability distribution is not considered at all. As evidence of the model's shortcomings, the Korean Air Force repairables management tends to stock large quantities of spare parts and components in order to avoid stockout situations.

III. OVERVIEW OF REPAIRABLE MANAGEMENT MODEL

A. INTRODUCTION

Inventory systems such as the one described in the previous chapter can be classified rather broadly as a multiechelon system with repair. Analytical studies of multiechelon systems have shown the computation in such models to be hard, so either simplifying assumptions or approximations are necessary. The introduction of the repair aspect into the system certainly complicates the structure of a model even at single echelon levels.

Suppose a repairable system, consisting of one Inventory Control Point (ICP), one stock point and one overhaul and repair activity controls the inventory of a single item. Demands from various tactical units are placed only at the stock point. The system has continuous updating of records, i.e., transaction reporting. When items wear out or fail, the tactical unit can either scrap the item or return it to the depot repair facility (DME, DMA, DMEC). After inspection, the depot can either scrap the item or repair and return it to the RFI inventory.

In this chapter, we will discuss various repairable inventory models based on two distinguishing characteristics. One is a deterministic model, the other is a stochastic model. In case of deterministic model, we will describe two models, "continuous supplement" model and "substitution" model. For the stochastic case, we will describe five models based on current usage in U.S military. Each description will include model formulation and solution techniques.

B. DETERMINISTIC INVENTORY MODEL

These deterministic inventory models were developed by David A. Schrady and others between 1966 and 1967. These deterministic inventory models are described in a research report for the U.S Navy repairable inventory management system [Ref. 5, 6, 7]. The first model calls for the repair activity to induct a batch of carcasses when the NRFI inventory level reaches a certain point. With a deterministic system, this rule insures regularly spaced repair inductions of fixed batch size, which is a simple process for the repair activity to manage. Repair batch sizes can be maintained if there is continuous supplementing of repaired RFI items with new procurement. The procurement order will be issued with enough lead time so that when the on-hand RFI stock drops to zero, a procurement quantity will arrive. The two inventories, RFI and NRFI, will have time histories as shown in Figure 4. Note that in this, the "continuous supplement" model, the procurement trigger is in the RFI inventory and the repair trigger is in the NRFI inventory. [Ref. 6, 7: pp. 9-10, pp. 392-393]

The second model is suggested by noticing that there is a trade-off between stock held in RFI condition and stock held in NRFI condition. NRFI carcasses are a legitimate resource because they require only repair to be restored to full usefulness. But the value of this resource is less than the value of the RFI resource by at least the cost of labor and replacement parts. Thus, if inventory is to be held in the system, it would be slightly cheaper to hold it in NRFI condition than in RFI condition. [Ref. 6, 7: p. 10, p. 393]

Notice that the "substitution" policy minimizes the RFI inventory while the "continuous supplement" policy minimizes the NRFI inventory [Ref. 6: p. 13]. The next section describes the mathematics of these two models.

1. Analysis of The Continuous Supplement Policy Model

a. Notation

Under the assumption of deterministic demand and lead times, it is not necessary to maintain a safety stock. Whenever the RFI inventory reaches zero, a procurement quantity will arrive. Thus, the system is never out of stock. Between procurement arrivals, depleting RFI stock is replenished with repaired items. Also, a repetitive system will be established regardless of the initial provisioning policy, so that it is sufficient to analyze only one cycle to determine system characteristics. Figure 4, shows basic characteristics of the "continuous supplement" policy model. The basic notation as follows [Ref. 5: pp. 12-22]:

D = annual demand rate

T_1 = procurement cycle

T_2 = repair cycle

t_1 = procurement lead time

t_2 = repair lead time

r_0 = field recovery rate

r_2 = overhaul and repair recovery rate

Q_1 = procured lot size

Q_2 = repaired lot size

h_1 = holding cost for RFI

h_2 = holding cost for NRFI

X_1 = reorder point for procurement

X_2' = reorder point for repair

n = number of repair cycles per procurement cycle, $n = T_1 / T_2$

A_1 = fixed procurement cost per one cycle

A_2 = fixed repair cost per induction

b. *Model Formulation*

The objective of the model is to determine an optimal procurement quantity Q_1^* and an optimal repair quantity Q_2^* that minimize the average annual cost. These optimal values, coupled with respective reorder points, X_1 and X_2, constitute an optimal operating doctrine. To determine the average annual variable cost, the costs per repair reorder cycle must be investigated. The product of per cycle costs and the number of cycles per year will then yield the average annual cost. The total cost for any given cycle T_1 is the sum of procurement, repair and holding costs.

Since there is only one procurement per reorder cycle, the variable order cost is the actual cost of the items ordered and can be expressed as Q_1C_1. The fixed procurement cost for one cycle is A_1 as mentioned. To determine the repair costs per cycle it is necessary to compute the number of repair cycles per procurement cycle ($n = T_1 / T_2$, n is an integer). In Figure 4:

$$T_2 = t_1 + t_2$$

where:

$$t_1 = KT_2 \ , \qquad O \leq K \leq 1$$
$$t_2 = (1 - K)T_2$$

The cost of items repaired per procurement cycle is C_2Q_2 and the fixed repair cost is A_2n, where A_2 is defined to be the fixed repair cost per induction. The holding costs per procurement cycle will be $h_1A_{T_1} + h_2A_{T_2}$, where A_{T_1} is the area under RFI curve and A_{T_2} is the area under the NRFI curve. To compute the area under RFI curve, consider Figure 5 showing RFI inventory for one procurement cycle. Since D is constant and known, the area of U, A_U, is given by:

$$A_U = \frac{1}{2}\, t_1 (Q_1 + a)$$

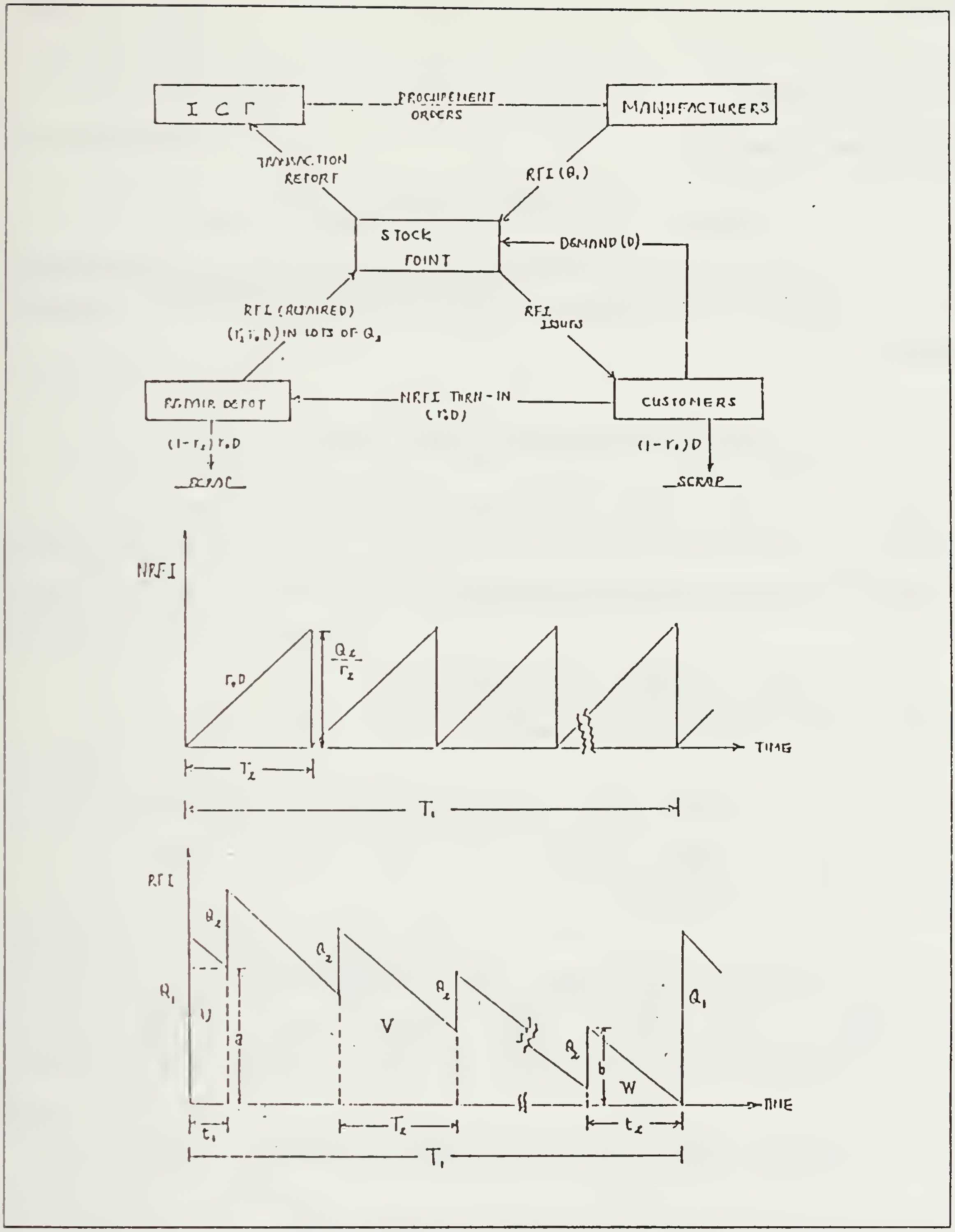

Figure 4. Repair Cycle and System for "Continuous Supplement" Model

where:

$t_1 = K T_2$

$a = Q_1 - D t_1$

The formula will reduce to:

$$A_U = (t_1 Q_1 - D t_1^2) / 2$$

Since n is an integer, the area of V is the sum of n-1 trapezoids each having one side of length T_2. To determine the area of each trapezoid, a recursive relation is developed. Let:

$$A_{V_i} = \text{area of the ith trapezoid in V (see Figure 4)}$$
$$= A_{V_1} + A_{V_2} + \ldots.. + A_{V_{n-1}}$$

where:

$$A_{V_1} = \frac{1}{2} T_2[2 Q_2 + 2 (Q_1 - t_1 D) - DT_2]$$

$$A_{V_2} = \frac{1}{2} T_2[4Q_2 + 2 (Q_1 - t_1 D) - 3DT_2]$$

therefore, the general formula for the area of V:

$$A_{V_i} = \frac{1}{2} T_2[2 i Q_2 + 2 (Q_1 - t_1 D) - (2i - 1)DT_2] \qquad i = 1,2,\ldots.,n - 1.$$

So the area of V is, $A_V = \sum_{i=1}^{n-1} A_{V_i}$:

$$A_V = \frac{1}{2} T_2[2Q_2\sum_{i=1}^{n-1} i + 2 (n - 1)(Q_1 - t_1 D) - DT_2\sum_{i=1}^{n-1}(2i - 1)]$$

$$= \frac{1}{2} T_2[Q_2 n (n - 1) + 2(n - 1)Q_1 - 2(n - 1)t_1 D - DT_2 n(n - 1) + DT_2(n - 1)]$$

$$= \frac{1}{2} T_2[2(n - 1)(Q_1 - t_1 D) + (n^2 - n)Q_2 - (n - 1)^2 DT_2]$$

Finally, area of W in Figure 4, A_W is easily calculated as follow:

$$A_W = \frac{1}{2} t_2$$

where:

$t_2 = (1 - k)T_2$

$b = nQ_2 + (Q_1 - t_1 D) - (n - 1)DT_2$

Thus, the area of W:

$$A_W = \frac{1}{2} T_2[nQ_2 + Q_1 - t_1 D - (n - 1)DT_2]$$

The total area under RFI curve is:

$$A_T = A_U + A_V + A_W$$

$$= t_1 Q_1 - \frac{1}{2} Dt_1^2 + \frac{1}{2} T_2\{2(n-1)(Q_1) - D\,t_1 + (n^2 - n)Q_2 - (n^2 - n)DT_2\}$$

Since n is an integer and the build up rate of NRFI items, $r_0 D$, is constant, the area under the NRFI curve is simply n times the area under the repair cycle curve is $T_2 Q_2 / 2r_2$. So the NRFI holding cost per procurement cycle is $nT_2 Q_2 h_2 / 2r_2$. The total cost per procurement cycle becomes:

$$K_{T_1} = Q_1 C_1 + A_1 + \frac{A_2 T_1}{T_2} + \frac{C_2 Q_2 T_1}{T_2} + \frac{h_2 Q_2 T_1}{2} r_2 + h_1 A_{T_1}$$

The total average annual cost is then:

$$K = \frac{K_{T_1}}{T_1} = \frac{Q_1 C_1}{T_1} + \frac{A_1}{T_1} + \frac{A_2}{T_2} + \frac{C_2 Q_2}{T_2} + \frac{h_2 Q_2}{2r_2} + \frac{h_1 A_{T_1}}{T_1}$$

Simplifying the total average annual cost:

$$K = \frac{A_1 RD}{Q_1} + C_1 RD + A_2 r_2 r_0 D + \frac{h_2 Q_2}{2r_2} + \frac{h_1 Q_1}{2} - h_1 k Q_2 + \frac{h_1 Q_2}{2}$$

where:

$T_2 = Q_2 / r_0 r_2 D$

$T_1 / T_2 = n, \quad n = 1,2,3,....$

$t_1 = kT_2 = kQ_2 / r_0 r_2 D$ for, $0 \le k \le 1$

$t_1 + t_2 = T_2$

$T_1 = Q_1 / 1 - r_0 r_2 D = Q_1 / RD$

$R = 1 - r_0 r_2$

Note that the terms $C_1 RD$ and $C_2 r_0 r_2 D$ are independent of Q_1 and Q_2, and hence do not affect the operating doctrine. Therefore it is appropriate to redefine the average annual cost of ordering, repairing and holding as follow:

$$K = \frac{A_1 RD}{Q_1} + \frac{A_2 r_0 r_2 D}{Q_2} + \frac{h_2 Q_2}{2r_2} + \frac{h_1 Q_1}{2} - h_1 k Q_2 + \frac{h_1 Q_2}{2}$$

From differential calculus the optimal Q_1 and Q_2 will be those that satisfy the equations,

$$\frac{\partial K}{\partial Q_1} = 0 \,, \quad \frac{\partial K}{\partial Q_2} = 0$$

Taking the partial derivatives results in:

$$\frac{\partial K}{\partial Q_1} = -\frac{A_1 RD}{Q_1^2} + \frac{h_1}{2}$$

$$\frac{\partial K}{\partial Q_2} = -\frac{A_2 r_0 r_2 D}{Q_2^2} + \frac{h_2}{2r_2} - kh_1 + \frac{h_1}{2}$$

Solving the equation to get the optimal procurement and repair quantities,

$$Q_1^* = \sqrt{\frac{2A_1 RD}{h_1}}, \qquad Q_2^* = \sqrt{\frac{2A_2 r_0 r_0^2 D}{h_2 + r_2 h_1 (1 - 2k)}}$$

2. The Substitution Policy Model

a. Notation

Notice that this model minimizes the RFI inventory. Figure 5 shows basic characteristics of the "substitution " policy model. The basic notation as follows [Ref. 6, 7: pp. 13-17, pp. 393-396]:

Q_P = procurement quantity

Q_R = repair batch size

d = demand rate

$(1 - r)$ = scrap rate, r is the recovery rate measured

t_P, t_R = procurement and repair lead times

A_P = fixed procurement cost per order

A_R = fixed repair batch induction cost per batch

h_1 = RFI holding cost

h_2 = NRFI holding cost

T = system cycle time

b. Model Formulation

Referring to Figure 5, define T_a as the time period during which inductions are suspended and the repair is simply accumulating NRFI carcasses. It may be determined that:

$$T_a = (Q_P + Q_R) / d$$

Next, let n be the number of inductions per cycle. In general, it will not be possible to insure that the last induction before T_a begins will reduce the NRFI stock to zero. The residual NRFI stock when T_a begins will be some fraction of the net loss in NRFI items per repair cycle, where the repair cycle is the time between regular consecutive inductions. The net loss of NRFI inventory over the period between successive inductions:

$$rd(Q_R / d) - Q_R = -Q_R(1 - r)$$

Thus, the residual when T_a begins will be some fraction of $Q_R(1 - r)$, call it $\beta Q_R(1 - r)$ where $0 \leq \beta \leq 1$. While the β factor is unavoidable due to the requirement that there be an integral number of repair batches in each cycle, we shall set $\beta = 0$ in subsequent developments.

Now the first batch after inductions are resumed takes the amount Q_R from the NRFI inventory. Subsequent inductions cause a net reduction of only $Q_R(1 - r)$ items. Thus, the amount of NRFI items available for the (n-1) inductions are $rdT_a - Q_R$ or $Q_R(r - 1) + rQ_P$. Dividing the last expression by $Q_R(1 - r)$ yield:

$$(n - 1) = \frac{Q_R(r - 1) + rQ_P}{Q_R(1 - r)} = -1 + (\frac{r}{1 - r})Q_P Q_R$$

or

$$n = (\frac{r}{1 - r})\frac{Q_P}{Q_R}$$

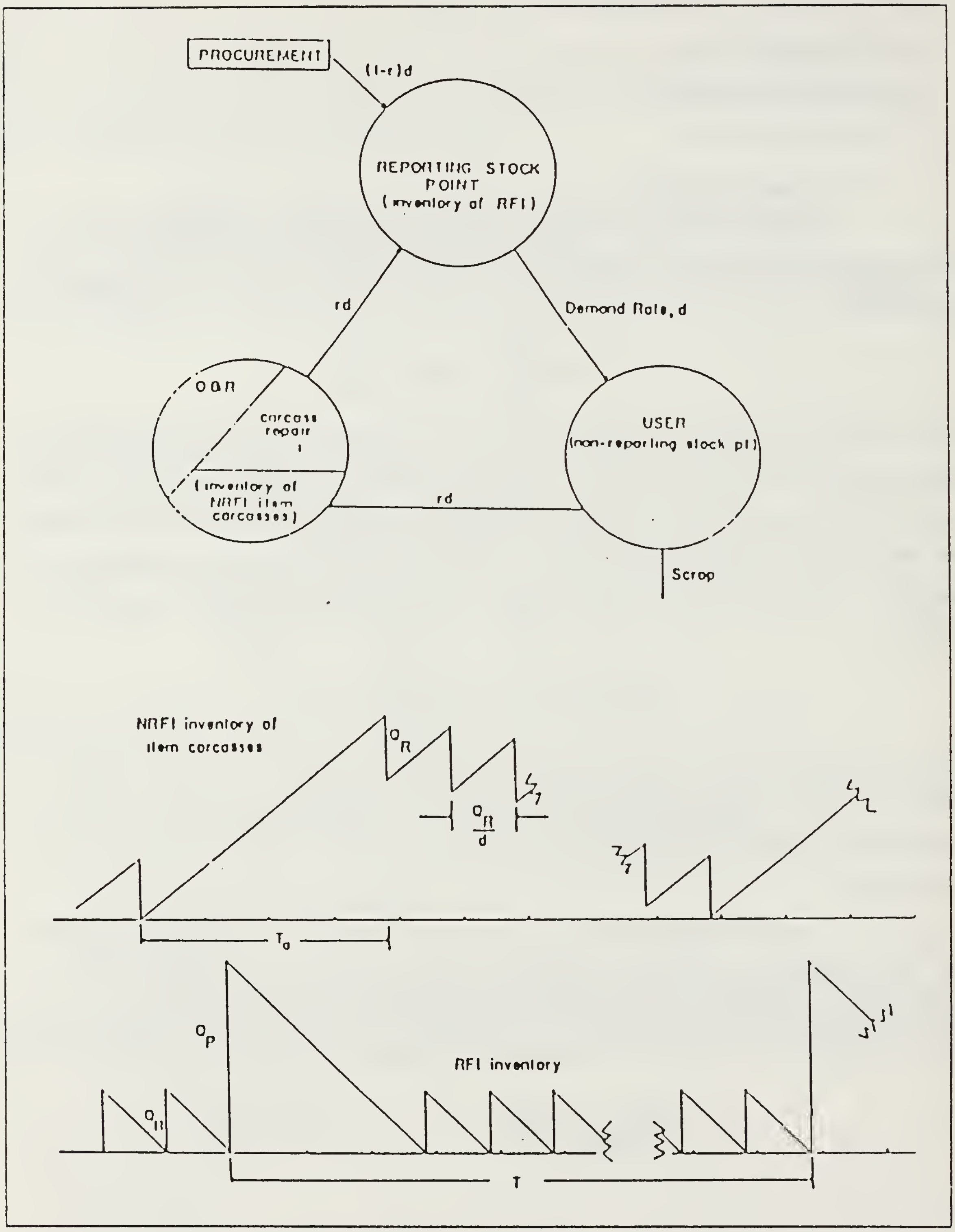

Figure 5. Repair Cycles and System for "Substitution" Model

The system cycle time is given by:

$$T = \frac{nQ_R + Q_P}{d} = \frac{Q_P}{(1-r)d}$$

where:

$n = (\frac{r}{1-r})Q_P Q_R.$

From the Figure 7, the area under the RFI curve, over one complete cycle A_1, is then:

$$A_1 = \frac{1}{2d}(\frac{r}{1-r})[Q_R Q_P + (\frac{1-r}{r})Q_P^2]$$

Referring again to Figure 7 the area the NRFI curve:

$$A_2 = \frac{1}{2}(\frac{r}{1-r})[Q_R Q_P + Q_P^2]$$

Now we get total cost per unit times expression:

$$\frac{TC}{T} = A_P \frac{d(1-r)}{Q_P} + \frac{A_R rd}{Q_R} + \frac{h_2 r}{2}[Q_R + (\frac{1-r}{r})Q_P] + h_2 r[Q_P + Q_R]$$

where:

$$T = \frac{Q_P + nQ_R}{d} = \frac{Q_P}{d(1-r)}$$

The total cost under substitution model:

$$TC = A_P + nA_R + \frac{h_1}{2d}\frac{r}{1-r}[Q_P Q_R + \frac{1-r}{r}Q_P^2] + \frac{h_2}{2d}\frac{r}{1-r}[Q_P Q_R + Q_P^2]$$

The optimal order quantities are obtained by setting the partial deriatives, with respect to Q_P and Q_R:

$$\frac{\partial TC}{\partial Q_P} = 0 \ , \ \frac{\partial TC}{\partial Q_R} = 0$$

Next we get new formula for optimal order quantities:

$$\frac{\partial TC}{\partial Q_P} = -\frac{A_P d(1-r)}{Q_P^2} + \frac{h_1(1-r)}{2} + \frac{h_2 r}{2}$$

$$\frac{\partial TC}{\partial Q_R} = -\frac{A_R r d}{Q_R^2} + \frac{h_1 r}{2} + \frac{h_2 r}{2}$$

The optimal order quantities for repair and procurement:

$$Q_P^* = \sqrt{\frac{2A_P d(1-r)}{h_1(1-r) + h_2 r}}, \qquad Q_R^* = \sqrt{\frac{2A_2 d}{h_1 + h_2}}$$

3. Summary and Evaluation

An important result of deterministic inventory model analysis is the realization that economic order quantities do not vary directly with demand but as the square root of demand. This nonlinear relationship could explain why many organizations experience inventory problems. Intuitive inventory policies are undermined by difficult-to-grasp nonlinearities. [Ref. 8: p. 141]

Although the models described in this section are evidently applicable to repairables management, they are fraught with many limitations. The reasonableness of model assumptions and their sensitivity to actual conditions determines the utility of any particular model. For example, the two models assume that the demand for a repairable item is known with certainty. Also stockouts either are not permitted to exist or are backordered and satisfied when replenishments are received.

In terms of the Korean Air Force repairable management system, the models described here are difficult to adapt to the Korean Air Force system. This is because of demand variability, relatively long procurement lead time, repair capacity and capability, a number of backorder situations, and current system management concept. The other important point is that the Korean Air Force often encounters NORS conditions which results in decreased operational availability. However, these two deterministic models do not deal with stockouts. These reasons didn't allow to use for the Korean Air Force repairable management system.

C. STOCHASTIC INVENTORY MODELS

As the weapon systems installed in modern aircraft become increasingly sophisticated and complex, repairable items represents an important subset of the total inventory of items which are managed by the military supply system.

In general, repairable items are supported by a two-echelon inventory and repair system. When a repairable item fails at the base level, it is returned to base supply and a new serviceable unit is issued from extra RFI stock of the base. If possible, the failed item is then repaired by the base maintenance organization and then stored in RFI conditions at base supply. Sometimes, however, the failed item must be returned to the repair depot where more sophisticated equipment and specialized skills are available to repair it.

When we consider the condemnation of repairables, there should be an inflow of newly manufactured items to depot level supply should look at the material flow of all echelons, and then, place a replenishment order to resupply the condemned repairables. At times, forward base locations will be supplied from another closely located base. This is called lateral resupply. For other items, a manufacturer may provide both the source of procurement for new assets and the source of repair for failed items.

The decisions concerning which maintenance levels will repair the failed items subsequently affects the supply support provided at the organizational level. If an item is repaired at the organizational level, repair equipment and maintenance personnel must be made available at that level. However, if the item is not repairable at that level, then the question is whether the item can be replaced at the organizational level. Organizational level repairables will normally be transferred to the next higher echelon of repair if the repairs cannot be accomplished at the organizational level. Similarly, repairables which cannot be repaired by the intermediate level are usually sent to the depot level for repair.

The difference between stochastic models and deterministic models is that if demands or future requirements are uncertain, then regardless of the stockage policy adopted there is generally some probability that available stock levels will be insufficient to meet demand [Ref. 9: pp. 187-188]. In this section, we will describe five stochastic models based on current usage.

1. Model Analysis

a. *Analysis of METRIC Model*

(1) Background. The METRIC model was developed over a period of years by a research group at the RAND corporation and presented in the literature by Sherbrooke (1968) and extened by Muckstadt (1973). METRIC was developed with the ultimate goal of implementation and a slightly modified version of METRIC was actually implemented by the USAF. [Ref. 10, 11, 12]

METRIC is a mathematical model of a base-depot supply system in which item demand is assumed to be compound Poisson with a mean value estimated by a Bayesian procedure. The model is also capable of determining base and depot stock levels for stock levels of a group of recoverable items. Its governing purpose is to optimize system performance for specified levels of system investment. It is designed for application at the weapon-system level, where a particular line item may be demanded at several bases and the bases are supported by one central depot. The support depot may vary by item as in the item-manager system or it may be fixed as in the weapon-system storage site concept. The general purposes of this model are optimization, redistribution and evaluation. [Ref. 13: p. 2]

The basic METRIC model considers a two-echelon system in which independent bases (lower echelon) are supported by a repair depot (upper echelon). At the occurrence of a failure (it could be more than one), the failed item is either replaced by available base stock or back ordered if the base stock is not available. The item is inspected to determine the extent of repair required. If the repair can be made at the base, the unrepaired item enters base repair. If the item cannot be repaired at the base level, it is shipped to the depot. Upon shipping the item to the depot, the base places an order with the depot for a replacement, so that the inventory position for item i at base j can be maintained.

(2) Mathematical Assumptions

1. *System Objective of Minimizing the Expected Number of Backorders:* The objective will be to minimize the sum of expected backorders on all recoverable items at all bases pertinent to a specific weapon system. Thus, unless all bases are identical, the expected number of backorders will vary by base. Expected backorders take a fixed period of time and add together the number of days on which any unit of any item at any base is backordered. In order to minimize the expected number of backorders one divides this number by the length of the period and taking the expected value. This yields a number that is independent of period length. This is the value we seek to minimize. [Ref. 14: pp. 126-131]

2. *Compound Poisson Demand:* We assume that demand for each item is described by a logarithmic Poisson process. Compound Poisson processes are generalizations of Poisson processes; the compound processes allow the flexibility of incorporating more parameters, yet retain the simple analytical properties of the Poisson. The logarithmtic Poisson is obtained by considering batches of demands where the number of batches follows a Poisson process and the number of demands per batch has a logarithmic distribution.

3. *Demand is Stationary over the Prediction Period:* It is assumed that the distribution of demand over some future period of interest is stationary.

4. *Repair Decision Depends on the Complexity:* The assumption is that the decision to repair a unit at base level or send it to the depot is a function only of the type of malfunction and the base maintenance capability.

5. *Lateral Resupply is Ignored:* When a unit is shipped from base to depot for repair, a serviceable replacement will be resupplied from the depot if possible. If the depot has no unit on the shelf, the base must wait until a unit emerges from depot repair.

6. *System is Conservative:* Consider a particular stock item demanded at base j. We assume that a unit of stock has a probability r_j of being repairable at base j, with a repair time drawn at random from a base repair distribution with mean A_j; a probability $(1 - r_j)$ of being depot repairable, with an order and shipping-time distribution having mean O_j and a depot repair distribution having mean D. This implies that there are no condemnations or that the system is conservative, as the name "recoverable item" suggests. A higher condemnation rate usually indicates that the item should be redesigned. The condemnation rate must be considered for procurement purposes, but the procurement process is not considered in the METRIC optimization.

7. *The Depot Does Not Batch Units of Recoverable Item for Repair:* The model assumes that depot repair begins when the repairable base turn-in arrives at the depot. This appears to be a reasonable approximation to current depot scheduling practice. Since METRIC economizes by buying fewer high-cost items, these are the items which are most likely to be in short supply.

8. *Demand Data from Different Bases Can Be Pooled:* We assume that demand from the several bases can be pooled in some manner so that a composite initial estimate of demand per flying hour can be obtained. The pooled estimate can be obtained by a simple averaging technique or a more sophisticated procedure such as exponential smoothing. METRIC multiplies this number by the flying hours per month for each item.

(3) Model Formulation. By mathematical assumptions, demand in this system follows a compound Poisson process. A compound Poisson process may be thought of as a series of customers who arrive following a Poisson process, each of whom can demand an amount that is independently distributed according to a compounding distribution. Assume that item i is stocked at each of base j, and the customers who place demand for the item at each base have a known mean arrival rate of λ_j, j = 1,2,3,......,J. When a customer arrives at base to place one or several demands, he turns in an equal number of carcasses. These carcasses can be repaired at base level with probability of r_{ij}, while $(1 - r_{ij})$ is the probability that they must be repaired at the depot. The arrival of carcasses from base j at the depot is described by a Poisson process whose mean is $(1 - r_{ij})$ times the mean of the Poisson customer arrival process at the base j. Therefore, the total demand at the depot for item i is compound Poisson, with mean customer arrival rate:

$$\lambda = \sum_{j=1}^{J} \lambda_{ij}(1 - r_{ij})$$

where:

λ_{ij} = mean arrival rate fot item i at base j

Let f_{ij} be the mean demand per customer at base j. Then, the mean depot demand rate for unit i is:

$$\theta = \sum_{j=1}^{J} \lambda_{ij} f_{ij}(1 - r_{ij}) = \sum_{j=1}^{J} \theta_{ij}(1 - r_{ij})$$

where:

θ_{ij} = the mean rate for item i at base j

In the special case of the logarithmic Poisson process, the probability that x customer demands are in the repair/supply process is negative-binomial with parameters q and K (Note: $K = \lambda T / \ln q$ where λ is mean customer arrival rate and T is average resupply time).

$$P(x \mid \lambda_{ij} T_{ij}) = (K + x - 1)! \frac{(q - 1)^2}{(K - 1)! x! q^{x+K}}$$

$$x = 0,1,2,......, \qquad q \geq 1, \qquad K \geq 0$$

where:

q = the variance to mean ratio of $P(x \mid \lambda_{ij} T_{ij})$

$K = \lambda_{ij} T_{ij} f_{ij} / (q - 1)$

T_{ij} = average resupply time for a demand for item i at base j.

A_{ij} = base repair cycle time

D = depot repair cycle time

O_{ij} = the order and shipping time

$\delta(S_O)$ = average depot delay

Then:

$$T_{ij} = r_{ij} A_{ij} + (1 - r_{ij})\{O_{ij} + \delta(S_O)\}$$

Since it takes an average of D time units for an arrival to complete the repair process, the probability distribution of the number of units in the depot repair cycle is compound Poisson with mean of λD. Hence, the expected number of units back ordered at the depot is:

$$BO(S_O \mid \lambda D) = \sum_{x > S_O} (x - S_O)\, P(x \mid \lambda D)$$

As mentioned in the beginning, the objective of METRIC is to minimize the sum of backorders for all item i and for all bases j within a budget constraint. Thus, the METRIC problem will be represented as follows:

$$\text{minimize} \sum_{i=1}^{I} \sum_{j=1}^{J} BO_{ij}(S_{iO}, S_{ij})$$

$$\text{subject to} \sum_{i=1}^{I} \sum_{j=1}^{J} C_i S_{ij} \leq C$$

$$S_{ij} \geq 0, \quad 1 \leq i \leq I, \quad 0 \leq j \leq J$$

where:

S_{ij} = the decision variables, stock for item i at base j

C = the total amount of budget available

C_i = the cost of item i

S_{io} = the depot stock for item i

(4) Solution Technique. The METRIC problem is solved by using the generalized Lagrange Multiplier method suggested by Fox and Landi [Ref. 15: pp. 258-261]. Let Φ be a Lagrange Multiplier associated with the budget constraint. The Lagrange function is written:

$$\sum_{i=1}^{I} \sum_{j=1}^{J} BO_{ij}(S_{ij} \mid \lambda_{ij} T_{ij}) - \Phi \sum_{i=1}^{I} \sum_{j=1}^{J} C_i S_{ij}$$

The auxiliary problem attempts to minimize this equation. By trial and error, we try to find the value of Φ which satisfies a given constraint. Therefore, we need to solve the above equation for several values of Φ, and choose that value of Φ for which the required resources are closest to the budget limit. Fox and Landi suggest a binary search procedure. Their computational experience was that at most six bisections were required to obtain budget allocations that were within one half of 1% of the original budget C.

The objective function is separable in the items. Dropping the subscript i in the original problem allows us to rewrite the equation as:

$$\min \sum_{i=1}^{I} BO_i(S_j \mid \lambda_j T_j) \; - \; \Phi C_i S_{ij} \; - \; \Phi C_i S_{iO}$$

Since $BO_j(S_i \mid \lambda_j T_j)$ is discretely convex for a given S_{iO}, the optimum base level is obtained by simply finding the smallest non-negative integer satisfying:

$$BO_j(S_i \; + \; 1 \mid \lambda_j T_j) \; - \; BO(S_j \mid \lambda_j T_j) \geq \Phi C_i S_{iO}$$

(5) Model Evaluation. The current Korean Air Force Logistics system's objective is maximizing operational availability subject to a budget constraint. This is similar to the METRIC model. The objective of minimizing the expected number of backorders is related to the objectives of the Korean Air Force Logistics system. However, two assumptions are distinctly violated. One is batch size repair policy is not used, the other is lateral resupply is ignored. Currently, these assumptions are not used in the Korean Air Force because of relatively long procurement leadtimes and repair capability limitations. It may be possible for the Korean Air Force computer resources to handle the data requirements for the METRIC model, but it is doubtful for actual usage. However, the METRIC model is obviously related to the Korean Air Force in terms of its basic concept and system objective.

b. Mod-METRIC Model

(1) Background. Mod-METRIC model was developed by Muckstadt to deal with problems which the METRIC approach did not consider. Mod-METRIC considers the relations in parts hierarchy and tries to solve this multi-indenture level problem. Mod-METRIC was implemented by the U.S. Air Force as the method for computing repairable stock levels for the F-15 weapon system. [Ref. 16: p. 472]

Most repairables contain subassemblies or other components which are also repairable. For example an aircraft engine, it may have modules for intake, combustion and exhaust. If an engine fails, it is replaced by a serviceable engine from base stock. The failed component is then repaired either at the base or depot level depending upon the complexity of repair. A serviceable module from the base stock, if available, will replace the failed module, and the repaired engine is placed in base engine stock.

(2) *Mathematical Assumptions.* The assumptions stated in METRIC are also applicable to Mod-METRIC except that Mod-METRIC assumes that the demand process is the simple Poisson process. [Ref. 16 pp. 475-476]

(3) *Model Formulation.* In METRIC, the objective is to minimize expected backorders for all items subject to an investment constraint. The Mod-METRIC objective, however, is to minimize the backorders for the end item, subject to an investment constraint on the total dollars allocated to the end item and its components [Ref. 16, 17: p. 475, p. 39]. This difference is caused by the hierarchical maintenance relationship between the module and the end item. As an example, an engine backorder indicates that an aircraft is missing an engine and is unavailable to perform its flying mission. Modules, on the other hand, are used only to repair engines. A backorder for a module only delays the repair of an engine. The impact of module backorders and engine backorders is clearly not the same.

Let T_i denote the average engine resupply time at a base. By the nature of repairables, T_i depends on several factors. When it is repaired at base level, T_i would be the time it takes to flow through the base maintenance system. If it is repaired at the depot, T_i consists of the time to place the depot order for a serviceable part and to receive the part from the depot, assuming a serviceable asset is on hand at the depot. However, when there are no serviceable assets on hand at the depot, an additional delay is included in the resupply time:

$$T_i = r_i B_i + (1 - r_i)\{A_i + \delta(S_0 D)\}$$

where:

r_i = the probability an engine will be repaired at base i

B_i = the average resupply time, given an engine is repaired at base i

A_i = the average order and ship time for an engine at base i

S_o = the depot engine stock

D = the average depot repair time

$\delta S_o D$ = the delay days per demand

$\delta S_o D$ can be derived in the following manner. The expected number of engines back ordered at the depot is:

$$BO(S_o|\lambda D) = \sum_{X>S_o} (X - S_o)P(X|\lambda D)$$

where:

$\lambda = \sum_{i=1}^{I}(1 - r_i)\lambda_i$

λ_i = the daily engine removal rate at base i

In other words, this expression is the expected number of units on which delay is being incurred at a random point in time. Dividing this expression by the expected number of demands per day yields a statistic which has the dimension of delay days per demand:

$\delta S_o D = B(S_o \mid \lambda D) / \lambda$

= expected backorders/expected daily demand

Further, B_i can be divided into two components. That is, B_i is equal to the average remove and replace time, given that the necessary module is available, plus the expected delay due to the unavailability of the module which is required to repair the engine. Then:

$$B_i = R_i + \Delta_i$$

where:

R_i = the average repair time at base i if modules are available

Δ_i = the average delay in base engine repair due to unavailability of a needed module

Further, assume that the engine should be repaired by the failure of module j. Then, Δ_{ij} is the expected delay in engine base repair time due to a back order on module j at base i. Thus:

$$\Delta_{ij} = \sum_{X_{ij} > S_{ij}} (X_{ij} - S_{ij})P(X_{ij} \mid \lambda_{ij}T_{ij}) / X_{ij}$$

where:

λ_{ij} = average number of daily removals of module j at base i

S_{ij} = stock level of module j at base i

T_{ij} = average resupply time for module j at base i

Then:

$$T_{ij} = r_{ij}B_{ij} + (1 - r_{ij})(A_{ij} + \delta_j D_j)$$

where:

r_{ij} = the probability that a failure isolated to module j will be repaired at base level

B_{ij} = average base repair time for module j at base i

A_{ij} = average order and ship time for module j at base i

D_j = average depot repair time for module j

$\delta_j = \sum_{X > S_{oj}} (X - S_{oj})P(X \mid \theta_j D_j) / \theta_j D_j$

S_{oj} = the stock level of module j at the depot

$\theta_j = \sum_{j=1}^{J} \lambda_{ij}(1 - r_{ij})$

Consequently, the expected delay in engine repair at base i due to module unavailability is:

$$\Delta_i = (1 / r_i\lambda_i)\sum_{j=1}^{J} \lambda_{ij}\Delta_{ij}$$

Thus, expression T_i represents all the system components including the depot engine and modules stock level, and the base module stock level. By using this relationship, the engine and module stock levels can be derived. Finally, the mathematical statement of the problem is:

$$\min \sum_{i=1}^{I} \sum_{X > S_i} (X_i - S_i)P(X_i \mid \lambda_i T_i)$$

$$\text{subject to } \sum_{i=1}^{I}(C_E S_i + \sum_{j=1}^{J} C_{ij}S_{ij}) + \sum_{j=1}^{J} C_j S_{oj} + C_E S_o \leq C$$

where:

S_i = stock level of base i

C_E = unit cost of an engine (end item)

c_j = unit cost of module j

C = dollar budget limit

(4) Solution Technique. Unfortunately, the equation above is not separable, because T_{ij} is a complex function of the S_{ij}. Thus, Muckstadt recommended that it should be broken down into two parts; the component subproblem and the end item subproblem [Ref. 16: p. 477]. Even after the break-down of the problems, however, it requires the solution of many subproblems each of which corresponds to a particular division of the available budget between components and end items. The solution procedure is as follows.

First allocate the budget C into C_1 and C_2 for components and end items repectively. Allocate C_1 among components so as to minimize the expected end items repair delays summed over all bases subject to the budget constraint C_1. This problem is mathematically represented as:

$$\min \sum_{j=1}^{J} r_j \lambda_j$$

$$\text{subject to } \sum_{j=1}^{J} (C_j S_{oj} + \sum_{j=1}^{I} C_j S_{ij}) \leq C_1$$

This problem can be solved using the METRIC technique. Given the result from this step, compute the average resupply time T_j for the components of each base. Then, allocate the remaining budget C_2 so as to minimize the expected end item base backorders. The METRIC budget allocation procedure may again be used. The steps provide a set of proposed stock levels upon a given allocation of the budget among the end items and components. These steps then are repeated several times using new values for C_1 and C_2 to establish the best allocation.

(5) Model Evaluation. Basically, the Mod-METRIC model has a similar structure to METRIC. All assumptions used in Mod-METRIC model are applicable to METRIC except for the compound Poisson demand. In other words, this model is the same as METRIC for the Korean Air Force repairable management system. The only disadvantage is that the Mod-METRIC model was developed for new weapon systems such as the F-15 aircraft. However, the Korean Air Force has a lot of non-standard

weapon systems. These non-standard weapon systems are causing problems such as long procurement leadtimes.

c. Dyna-METRIC Model

(1) Background. Dyna-METRIC was developed by the RAND Corporation to provide an analytic method for studying the transient behaviour of component-repair and inventory systems under time-dependent operational demands and logistics decisions like those that might be experienced in wartime [Ref. 14, 18]. Note that the past work regarding the repairable item stockage prior to Dyna-METRIC only dealt with a steady state inventory system with constant average demand and service rates. These steady state assumptions may provide a good approximation during peace time operations. But in wartime demands for components may suddenly increase very much relative to the previous peacetime operation and then may decrease gradually or, in some case, drastically due to attrition in the system. [Ref. 14: pp. 1-6]

A key characteristic of Dyna-METRIC is its ability to deal with the dynamic or transient demands placed on component repair and inventory support caused by time variables in a scenario that includes sortie rates, mission changes, phased arrival of component repair resources, interruptions of transportation, and the like, all of which would be experienced in wartime. It computes how given resource levels and process times would contribute to the wartime capability. By exploiting the mathematical structures of its underlying equations, Dyna-METRIC suggests the alternative cost effective repair or stockage resource purchases which would achieve a target aircraft availability goal throughout the wartime scenario.

Dyna-METRIC considers a three echelon inventory repair system. Each base has an in-house repair facility which may have various test and repair capabilities. This base repair facility may be supported by several Centralized Intermediate Repair Facilities (CIRFs). Each operating base is capable of doing only limited types of maintenance, usually limited to simple removal and replacement operations at the flight line. It should be noticed that some of the bases have a CIRF while others do not have direct flows of parts to the depot. A depot is represented as existing outside of the model. It is seen from the model's point of view, as an infinite source of supply located some order and ship time away.

(2) Mathematical Assumptions. The major assumptions of Dyna-METRIC which distinguish it most from the others are shown below.

1. Demand for items are generated by a nonhomogeneous Poisson process with intensity function m(t), and mean value function $r(t) = \int m(s)\, ds$. The functions,

m(t) and r(t), will be defined later. The t denotes an arbitrary time. Thus, the demand process is dynamic.

2. The repair process is independent of the arrival process and has slack repair capacity so that each repairable item demanding repair immediately receives services with average service time based on the function F(s,t). F(s,t) will be defined later.

3. No more than one subcomponent can fail or be demanded in the repair of each assembly.

(3) Time Dependent Pipeline Equations. Since the major objective of the system is to avoid the loss of aircraft mission capability due to a shortage of correctly functioning components on the aircraft, it is necessary to compute the number of components awaiting repair, being repaired, being on the way to and from another echelon of repair, and partially repaired but awaiting spare parts. Each state is a pipeline segment is which characterized by a delay time that arriving components must spend in the pipeline before exiting the segment. The model expands each component's expected pipeline size into a complete probability distribution for the number of components currently undergoing repair and on order, so the probability distribution for all components can be combined to estimate aircraft availability and sorties. [Ref. 14: pp. 7-23]

Under the assumptions that the probability distribution of repair time is independent of the failure process, the average number of components in the repair pipeline will be:

$$\lambda_{ss} = dT$$

where:

d = average daily failure rate

T = average repair time

With the further assumption that demand has a Poisson probability distribution, the probability that there are K components in the pipeline at any point in time would be:

$$P(\text{ K in pipeline }) = \lambda_{ss}^{K} e^{-\lambda_{ss}} / K!$$

However, in Dyna-METRIC the demand is a function of time so that:

$$
\begin{aligned}
d(t) = &(\text{failure per flying hour})\\
&\times(\text{flying hour sorties at time t})\\
&\times(\text{number of sorties day per aircraft at time t})\\
&\times(\text{quantity of the component on the aircraft})\\
&\times(\text{percentage of aircraft with the component})
\end{aligned}
$$

Also, in place of a constant average repair time, T, the dynamic model uses the probability that a repair started at time s is not completed at time t. That is:

$$
\begin{aligned}
F(t,s) &= \text{Probability(component entering at s is still in repair at t)}\\
&= \text{Probability(repair time} > \text{t-s when started at s)}
\end{aligned}
$$

The average number of components in the pipeline is derived by combining those two functions. Consider only those components that arrived in an interval of time, Δs, centered at time s. Then:

$$\Delta\lambda(t,s) = d(s)\, F(t,s)\Delta s$$

where:

$\Delta\lambda(t,s)$ = expected number of components in the repair pipeline

$d(s)$ = daily failure rate at time s

$F(t,s)$ = Probability that a component is not out of repair by time t

Δs = interval of time centered at s

If we assume that the number of failures arriving in the interval Δs is independent of the number of failures arriving in similar intervals centered at other time other than s and F(t) is independent of the probability distribution generating the demand rate, then:

$$\lambda(t) = \sum_{s \le t} d(s)\, F(t,s)\, \Delta s$$

Further assume that Δs is very small, so that:

$$\lambda(t) = \int_0^t d(s)\, F(t,s)\, ds$$

With the additional assumption that the component failure probability distribution is Poisson, $\lambda(t)$ is the mean of a time varying (nonhomogeneous) Poisson process. That is, the probability of K components in repair at time t is:

$$P(K) = \lambda(t)^K e^{-\lambda(t)} / K!$$

where:

$$\lambda(t) = \int_0^t d(s)\, F(t,s)\, ds$$

(4) Time Dependent Component Performance Measure. The component measures typically computed by the Dyna-METRIC model are [Ref 14: pp. 24-29]:

R(t) = ready rate at time t

FR(t) = fill rate at time t

EB(t) = expected back orders

VBD(t) = variance of the backorders

DT(t) = average cumulative demands by time t

S(t) = supply level at time t

The ready rate is given by:

$$R(t) = \sum_{K=0}^{S(t)} P\{(K \mid \lambda(t))\}$$

Since the definition of the fill rate is the probability that a component will be available when a demand is placed, it is therefore the probability that demands have left at least one component available, that is, the sum of the probabilities of demands less than the stock level. Expected backorders are given by:

$$EB(t) = \sum_{K>S(t)} \{K - s(t)\} P\{K / \lambda(t)\}$$

$$= \lambda(t) - s(t) + \sum_{K=0}^{S} (t)\{s(t) - K\} P\{K / \lambda(t)\}$$

For K greater than s(t), there will be backorders of $\{K - s(t)\}$. The probability of any demand level, that is K, is $P\{K / \lambda(t)\}$, and the expected value of the backorders is merely the product of the various values the backorders can take on times the probability of a demand at that given value. The variance in backorders is given by:

$$VB(t) = \sum_{K>S(t)} \{K - s(t)\}^2 P\{K / \lambda(t)\} - \{EB(t)\}^2$$

(5) *Time Dependent Optimal Determination of Spare Parts.* The fact that pipelines have time-dependent probability distributions means that the optimal mix of spare components at one point in time may not be the optimal mix at another. Thus, the approach to take is to compute, for each time period of interest, the marginal increase in spare parts to achieve a given capability over those already input or determined for a previous time. In determining the supply level, the model attempts to provide enough spare parts to give the desired confidence at the lowest cost at each point in time of interest. Thus, the objective function is to minimize the total cost of spare parts.

Let:

S_i = the spare parts level for component i

C_i = the unit cost of component i

α = the desired confidence level

K_n = the non-mission capable rate not to be exceeded

$P(K_n,S)$ = the probability that the non-mission capable rate is less than K_n given a stock level S

I = types of repairables required on each aircraft

Then, the problem to solve is:

$$\text{minimize} \sum_{i=1}^{I} C_i S_i$$

$$\text{subject to } P(K_n,S) \geq \alpha, \quad S_i \geq S_{io}$$

where:

S_{io} = the input stock level or previous time optimization stock level for component i

Assuming complete cannibalization, $P(K_n,S)$ equals:

$$P(K_n,S) = \prod_{i=1}^{I} P^i(Q_i K_n)$$

where:

$$P^i(Q_i K_n) = \sum_{K=0}^{S_i + Q_i K_n} P_i(K)$$

$P_i(K)$ = the probability of exactly K failures of component i

The necessary condition for the performance constraint to be met is to have, $P^i(Q_i K_n) \geq \alpha$, for each i. Then marginal analysis is used to determine the best mix of additional components to achieve the desired goal. This process proceeds by investing in one additional component at a time which is selected by finding the component that gives the largest increase in the logarithms of the confidence level at the lowest cost. That is, we determine:

$$\Delta_i ln\, P\,(K_n,S)\ /\ C_i$$

where:

$$\Delta_i\, ln\, P\,(K_n,S) = ln\{P(K_n, S^i)\ /\ P(K_n,S)\}$$

$$S^i = (S_1, S_2, \ldots, S_{i+1}, \ldots)$$

The component for which supply is increased one unit is the one whose index solves; max $\Delta_i\, ln\, P(K_n,S)\ /\ C_i$. This process continues until the given confidence level is achieved. At this point, the resulting value of S is the efficient solution of the base stockage problem.

(6) Model Evaluation. The Dyna-METRIC model is relatively hard to adapt for the Korean Air Force. Especially since this model assumes that each repairable item needing repair immediately receives service. This does not occur in the Korean Air Force. Currently, the Korean Air Force applies a batch repair policy for repairables, except in case of NORS condition aircraft. This is a serious violation of the assumption of Dyna-METRIC. So, the Dyna-METRIC model is difficult to use for the Korean Air Force repairable management system without using a continuous repair policy.

d. Mathematical Models Used In The Navy

(1) Background. The Uniform Inventory Control Program (UICP) was developed in August 1965 to provide a standard system to be used at all U.S Naval

Supply Systems Command (NAVSUP) ICPs. The Fleet Material Support Office (FMSO) under the direction of NAVSUP is responsible for the system design, ADP analysis, programming and documentation of UICP. The development of the UICP formulas for inventory levels follows the approach used by Hadley and Whitin. [Ref. 13, 19]

(2) Mathematical Assumptions

1. It is a continuous review system. Wholesale inventory levels requirements and assets are known by the Inventory Control Point (ICP) at all times. [Ref. 13, 19: pp. 162-165, Chapter 3 Appedix A]
2. It is a steady state environment. The key characteristics of the items managed by the ICP are assumed to be constant over the forecast period. These characteristics include the forecasted average values and variances of the random variables of the rate of customer demand, procurement leadtime, production leadtime, depot repair times, depot repair survival rate and the rate of carcass returns.
3. An order for procurement or repair is placed when the assets reach the reorder level or the repair level.
4. Customer demands and carcass returns do not occur in more than one unit per transaction.
5. The unit procurement cost or repair cost of an item is independent of the magnitude of order quantity or repair quantity.
6. The cost of a backorder and the time-weighted cost of a backorder can be accurately quantified.
7. The reorder level and repair level are always non-negative.
8. The cost to hold one unit of stock in the inventory is proportional to the unit cost of the item.
9. No interaction exists among families of items or individual nonfamily items or both. Each family or nonfamily item's inventory levels requirements are calculated independently of those of families or nonfamily items.
10. The optimal inventory levels are determined by minimizing an average annual variable costs equation composed of order cost plus holding costs plus shortage costs.

(3) UICP Depot Level Repairables (DLRs) Procurement Model. The repairables procurement model starts with a total variable cost (TVC) equation which is to be minimized. A notable difference from the model for consumables is the inclusion of receipt of RFI assets from a repair process in the DLR model.

(a) Ordering Cost

Let:

A = administrative cost to order

D = forecasted quarterly recurring demand

B = forecasted quarterly regenerations

Q = economic order quantity

Then, $4(D - B)/Q$ is the expected number of procurements per year. Thus, the annual ordering cost is given by $4(D - B)A/Q$.

(b) Holding Cost

Let:

I = percent cost per dollar of inventory held annually

C = item cost (replacement)

L = procurement leadtime

T = repair turnaround time

R = repair level

F(x) = the function of probability distribution of leadtime demand

The mean demand during a procurement leadtime is given by:

$$DT + (D - B) \times (L - T)$$

Thus, holding cost is given by:

$$IC[\frac{Q}{2} + R - \{(D - B) \times L + B \times T\} + \int_{x \geq R} (x - R)F(x)\,dx]$$

let:

λ = shortage cost per requisition short

E = military essentiality weight

F = quarterly requisition rate

Then:

$$\frac{(\lambda E)\{4(D - B)\,/\,Q\}F}{D\int_{x \geq R} (x - R)\,F(x)\,dx}$$

It equals the cost of the expected number of backorders in a year. The TVC equation is symbolized by:

$$TVC = (D - B)A / Q$$

$$+ IC[Q/2 + R - \{(D - B) x L + B x T\} + \int_{x \geq R} (x - R)F(x)\, dx]$$

$$+ (\lambda E)[4(D - B)/Q]\, F / D \int_{x \geq R} (x - R)F(x)\, dx$$

Then, by setting dTVC / dQ = 0:

$$Q = \sqrt{[8(D - B)(A + \lambda EF / D)\int_{x \geq R} (x - R)F(x)\, dx / IC]}$$

Also, by setting dTVC / dR = 0, we find:

$$\int_{x \geq R} (x - R)F(x)\, dx = \frac{QICD}{\{QICD + 4\lambda EF(D - B)\}}$$

Because the expression $\int_{x \geq R}(x - R)F(x)\, dx$ is the cumulative distribution for leadtime demand, this is the quantity defined as RISK. Note that since Q and R are related, the reorder quantity Q cannot be solved independently. Thus, UICP approximates Q by using a variation of the economic order quantity formula:

$$Q = \sqrt{\frac{8(D - B)A}{IC}}$$

Then, $QICD / \{QICD + 4\lambda EF(D - B)\}$ can be computed for RISK determination.

(4) UICP Depot Level Repairables Repair Model. The repair model also starts with a total variable cost equation viewed largely independently of the procurement problem. Note that its time horizon is the depot level repair turn around time. The total variable cost equation for the repair model is the sum of the order cost, holding cost and backorder cost.

Let:

Q_2 = economic repair quantity

A_2 = repair administrative order cost

C_2 = repair price

R_2 = repair level

$F_2(x)$ = probability distribution of demand during during repair turnaround time

λ_2 = repair shortage cost

Then:

$$TVC = 4\,min(D,A)A_2 \,/\, Q_2$$

$$+ \; IC_2\{\frac{Q_2}{2} + R_2 - (D\,X\,T) + \int_{x \geq R_2} (x - R_2)F_2(x)dx\}$$

$$+ \; \lambda_2 E\{4\,min(D,B) \,/\, Q_2\}F \,/\, D\int_{x \geq R_2} (x - R_2)F_2(x)dx$$

By setting $\partial TVC \;/\; \partial Q_2 = 0$:

$$Q_2 = \sqrt{8\,min\,(D,B)A_2 + \lambda_2 EF \,/\, D\int_{x \geq R_2} (x - R_2)F_2(x)dx \,/\, IC_2}$$

Also, by setting $\partial TVC \;/\; \partial R_2 = 0$:

$$\int_{x>o} F_2(x)dx = Q_2 IC_2 D \,/\, Q_2 IC_2 D + 4\lambda_2 EF\,min(D,B)$$

Again, Q_2 and R_2 are related. The UICP model approximates Q_2 as follows:

$$Q_2 = \sqrt{8\,min\,(D,B)A_2 \,/\, IC_2}$$

Then, $Q_2 IC_2 D \,/\, Q_2 IC_2 D + 4\lambda_2 EFB$ can be computed by using the above results.

(5) Integrated Repairables Model. As stated earlier, the requirements computed by the procurement and repair models are accomplished independently of each other. As a result, this leads to a carcass constrained situation. That is, the computed procurement inventory level for an item does not provide sufficient carcasses to allow repairs at the computed repair inventory level. To solve this problem, Naval Supply System Command (NAVSUP) has made some changes. Under the model integration, there is only one RISK formula:

$$RISK = IC_3D / IC_3D + \lambda FE$$

where:

$$C_3 = (B/D)(C_2) + (1 - \frac{B}{D})(C)$$

Also, rather than using a procurement leadtime or a depot level repair turnaround time, it is uses an average acquisition time as the horizon for computing the safety level. The average acquisition time (L_2) is defined by:

$$L_2 = (1 - B/D)L + (B/D)T$$

It is clear that L_2 is the weighted average of the procurement leadtime and the repair turnaround time because D-B represents the quantity to be procured and B represents the quantity from the regeneration.

(6) Model Evaluation. For the UICP model, three major problems exist. The first problem is that UICP models is a continuous review inventory system. The Korean Air Force repairable management system applies a periodic review. The second problem is that UICP assumes that no interaction exists among failures of items. Finally, the optimal inventory level for UICP model is determined by minimizing annual variable cost (order costs plus handling costs plus shortage costs). However, the Korean Air Force does not have the same objective.

e. Availability Centered Inventory Model

(1) Background. ACIM was developed by CACI Inc. under the sponsorship of the Ship Support Improvement Project, Naval Sea System Command, PMS-306, and aproved in March 1981 by the Chief of Naval Operations for use in determining consumer level stockage quantities for selected equipment [Ref. 20: pp. 1-2]. However, this model was initially used as a part of a larger model (Logistics Support

Economic Evaluation Model) which provided necessary inputs and enabled comparisons with other Navy stockage policies. After this, successive refinements for the simplification of the solution procedure and associated computer programs have been made for several years.

This model was originally designed to calculate inventory levels for all items in the parts breakdown of an equipment and at all stockage facilities in a multi-echelon support system. Thus, ACIM is capable of computing levels for all ships, intermediate maintenance activities, and depots that use or support the equipment. However, this model is mainly used in the provisioning process to compute shipboard allowances to achieve specified weapon system readiness levels which have not been achieved with the standard protection level models.

(2) Availablity Measure. ACIM recognizes that the purpose of a supply system is to provide sufficient support so that a weapon system is operational when it is needed. The terminology used to described this goal is operational availability (A_o). ACIM defines A_o by the following formula [Ref. 21: p. 5]:

$$
\begin{aligned}
A_o &= \text{up time} / (\text{up time} + \text{down time}) \\
&= \text{MTBF} / (\text{MTBF} + \text{MTTR} + \text{MSRT})
\end{aligned}
$$

A_o may also be interpreted as the probability that the equipment is in an operable condition at a random point in time. Among the three factors of A_o, the MTBF and MTTR are system parameters outside the control of the supply system and are viewed as constraints. MSRT is the only term which depends on stockage postures, it is therefore the one that the ACIM model focuses on to achieve a given value for A_o.

(3) Mathematical Assumptions

1. All parts are organized in terms of equipment with a top-down breakdown that can be represented as an arborescent network. Any part may be totally consumable, totally repairable, or any mix thereof. [Ref. 21: pp. 10-11]
2. Stockage and maintenance facilities are organized in a hierarchical structure according to supply/ maintenance flows which can be represented as an arborescent network as illustrated below. Each facility has a colocated maintenance and supply capability. The facility at the top of the structure is assumed to have an infinite supply of all items.
3. External demands upon supply are stationary and compound-Poisson distributed.
4. All stockage locations use a continuous review, (S-1,S) ordering policy.

5. Mean Time to Repair (MTTR) is defined to include all equipment downtimes that are not supply related.
6. There is no lateral resupply (transshipment) among bases.
7. Items repaired at any location are assumed to be returned to collocated stocks for issue.
8. If, for a given facility in the network, the stocks are physically distributed in several places, it is assumed that the resupply time for direct customers (next lower echelon) is independent of the location.
9. The order policy assumption precludes consideration of economies of scale for resupply. That is, all ordering is on a one for one basis.

(4) Model formulation. The goal of ACIM is to maximize the operational availability (A_o) of a weapon system subject to a given inventory budget. With the definition given above of A_o and with the view that MSRT is the only term which is affected by the stockage decision, the developers of ACIM argue that the allocation which maximizes A_o is equivalent to the allocation which minimizes MSRT. ACIM therefore actually attempts to minimize MSRT subject to given constraints.

Let i be an arbitrary item in equipment e (which may be e itself). Let u=0 represent an arbitrary facility in the support system and u=1,2,3,...., represent facilities at the next lower level, i.e. those facilities that submit items for repair directly to or obtain resupply from facility o. Then, the objective can be explicitly stated as follows:

Find values for S_{kv} which minimize D_{iu} for all user locations u:

$$\text{subject to } \sum_{k,v} C_k S_{kv} = B$$

where:

C_k = unit cost of item k

B = given budget for spares procurement

D_{iu} = expected delay per demand upon inventory for for item i at location u

S_{kv} = the level of inventory for item k at location v

D_{iu} is one of the components of M_{iu} which is defined as the mean time to return a failed unit of item i at location u to a serviceable condition. M_{iu} is given by:

$$M_{iu} = D_{iu} + T_{iu}$$

where:

D_{iu} = expected delay per demand upon inventory for for item i at location u

T_{iu} = mean time to repair item i at user location u

D_{iu} in turn is given by:

$$D_{iu} = (1 / \lambda_{iu}) \sum_{X \geq S_{iu}} (X - S_{iu}) P(X : \lambda_{iu} T_{iu})$$

where:

S_{iu} = stock level of item i at location u

λ_{iu} = expected number of demands upon inventory for item i at location u

$P(X : \lambda_{iu} T_{iu})$ = probability of X units of stock reduction for item i at location u

T_{iu} = mean resupply time for item i at location u

T_{iu} is given by:

$$T_{iu} = (L_{iu} + L^{*}_{iu}) + (1 - r_{iu})(R_{iu} + R^{*}_{iu})$$

where:

r_{iu} = probability that a demand for item i upon inventory at location u

L_{iu} = average resupply leadtime assuming stock is is available

L^{*}_{iu} = additional resupply leadtime due to expected shortage at the resupply source

R_{iu} = average shop repair cycle assuming availability of spares for items within i

R^{*}_{iu} = additional shop repair cycle due to expected shortage of spares items within i

Since ACIM assumes that MTBF and MTTR are independent of the stockage policy, minimizing D_{iu} is assumed to maximize A_{eu} (operational availability of a equipment at location u).

(5) Solution Technique. Assume that initial values for S_{iu} are given for all items and locations. These may all be zero or some minimum value given by policy or current assets. Then compute the MSRTs for all items.

ACIM calculates what the new MSRT would be if one additional unit of stock were placed against that particular item. Subtracting the new MSRT from the old MSRT and then dividing by the unit cost of the item provides the model with a value which is multiplied by the item's demand to determine a selection-rank. After the selection number is calculated for each item, one unit of stock is added to the candidate with the highest selection rank number. The operational availability (A_o) is calculated and if the target A_o has not been achieved, the model continues the same procedure.

(6) Model Evaluation. As with the UICP model, three major violations of the basic assumptions of the ACIM model exist. The first is that ACIM assumes that you have a continuous review system. The second is that ACIM assumes there is no lateral resupply. Finally, ACIM assumes that the stocks are physically distributed at several locations. Obviously, the Korean Air Force supply system does not require several physical locations, even though the system objective is to maximize operational availability.

D. SUMMARY

Throughout Section B and C of this chapter, we have reviewed the various inventory models and theories for repairable items which are currently in use in the military services, or in the process of being evaluated. All of the assumptions and the mathematical formulations of the models were stated and discussed.

IV. MODEL PROPOSAL FOR THE KOREAN AIR FORCE

A. INTRODUCTION

In Chapter II, we summarized the current Korean Air Force repairables management system and repair process. The general structure of repairables management in the Korean Air Force is similar to the structure assumed by several of the models described in Chapter III.

In this Chapter, we describe a proposed inventory control process for the Korean Air Force. This process is based partly on queueing models, and partly the Wilson-Harris economic order quantity model.

B. THEORETICAL BASE FOR THE MODEL PROPOSAL

1. Notation

c = number of identical repair channels

μ_i = average repair rate per repair channel

α_i = average failure rate of an individual unit of a repairable item

N_i = random variable describing the steady state number of NRFI units of item i

P_n = steady state probability that there are n NRFI units

2. The M/M/1/K/K Queueing System

This model is a limited source queueing model in which there are only K customers. It is variously called the machine repair model, the machine interference model, or the cyclic queueing model. It is one of the most useful of all queueing theory models. One way to view this model is shown in Figure 6. [Ref. 22: pp. 186-190]

The population of potential customers for this queueing system consists of K identical devices, each of which has an operating time of O time units between breakdowns, O having an exponential distribution with average value $1/\alpha$. The one repairman repairs the machines at an exponential rate with an average repair time of $1/\mu$ time units. The operating machines are outside the queueing system (outlined by the dashed lines) and enter the system only when they break down. The queueing system always reaches a steady state because there can be no more than K customers in the system (one machine being repaired and K-1 waiting for repairs).

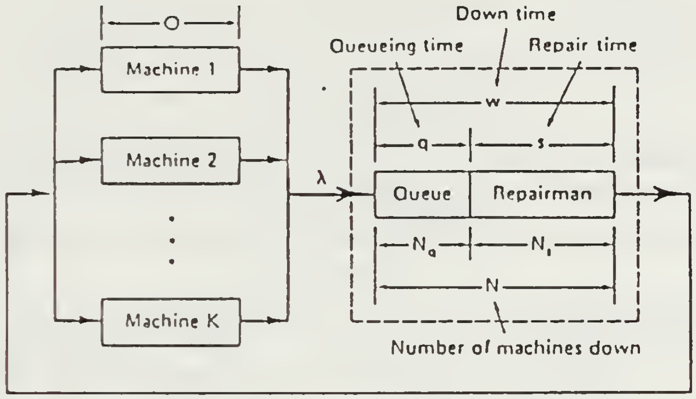

Figure 6. Queueing System with One Repairman (M/M/1/K/K)

When n of the machines are down (not operating), then K-n of them are operating and the time until the next machine breaks down is the minimum of K-n identical exponential distributions with parameter (K-n) α.

3. The M/M/c/K/K/ Queueing System

This queueing system is similar to the machine repair model considered in the section above except that we have c rather than one repairman, where $c \leq K$, as shown in Figure 7. [Ref. 22: pp. 190-192]

C. DEVELOPING A MODEL FOR THE KOREAN AIR FORCE

1. Application Conditions

1. Supporting D items, i.e., we want D items to be available at all times. In this case, D represents the number of aircraft which the Korean Air Force wants to have available at all times.

2. P(Successful Repair) is close to 1. When P(successful Repair) = 1, we have a pure machine repair queueing system. When P(Successful Repair) = 0, we have a consumable item whose management is best accomplished using standard methodologies from inventory theory. The sample data collected from the Korean Air Force for this study indicated that P(Successful Repair) = 0.98 or higher for all repairable items examined. For this reason, the proposed model is based partly on the machine repair queueing model. The data base used for the study was obtained from

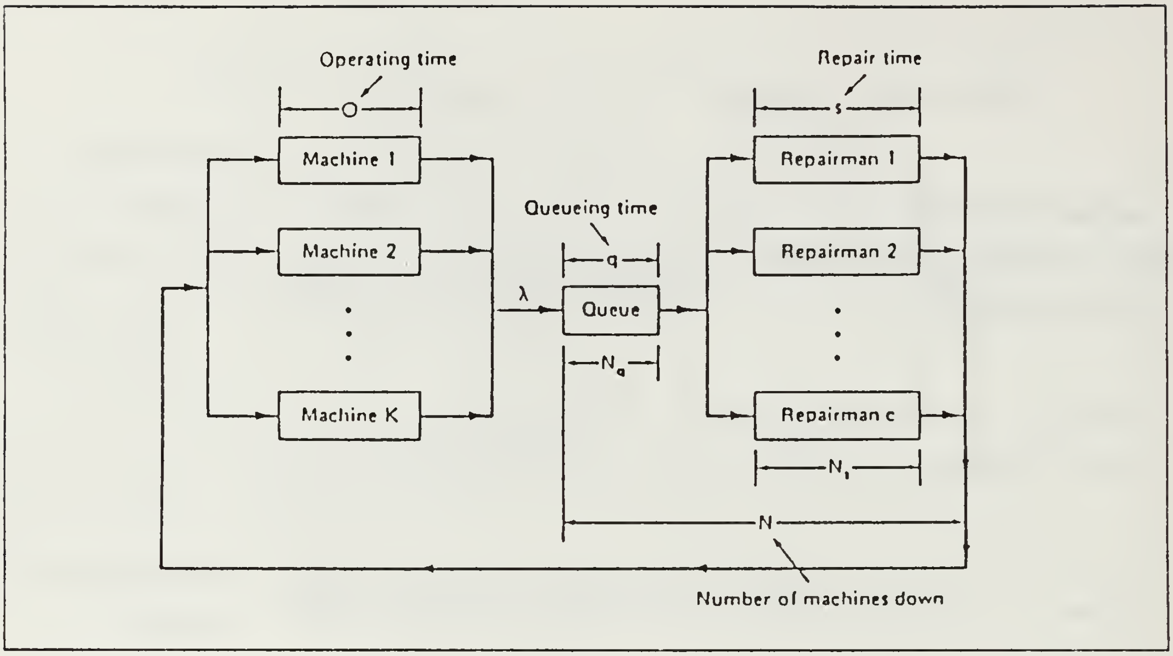

Figure 7. Queueing System with c Repairman (M/M/c/K/K)

the KAFLC during the 1984-1988. Table 3 shows the mean probability of successful repair based on the sample data.[6]

Table 3. P(SUCCESSFUL REPAIR) COMPUTED FROM SAMPLE DATA

Year A/C	84	85	86	87	88	Average
F-16	NA	NA	1.000	1.000	1.000	1.000
F-5	0.988	0.980	0.987	0.986	0.984	0.985
F-4	0.986	0.987	0.986	0.976	0.987	0.984

3. Conditions close to the M/M/1/K/K queueing system hold. Because, there are a number of repairmen in repair depot, it might be reasonable at first to assume that the M/M/c/K/K model applies. However, most repairs require specialized skills held by few people for a given repairable part. Further, the repair depot is staffed and scheduled so that there is little overall excess capacity. As a result, there is little change in the repair process output rate when the second, third, fourth, etc. unit backs up in the repair queue.

4. Steady state has been achieved.

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6 The sample data list appears in Appendix A and B

2. Model Formulation

This proposed model consists of 3 steps. The first step computes a minimum population size K_i for the ith type of repairable item. Population refers in this case to the installed material plus the stored RFI material plus the NRFI material awaiting repair. In other words, all material, both good and broken.

Once the minimum population size K_i is chosen, an attrition buy safety level S_i is chosen. This safety level is used to insure that the actual population size usually stays above K_i during the period when the system is awaiting the arrival of an attrition buy.

The last step is to compute the size of an attrition buy itself. This Q_i^* is computed using the Wilson-Harris economic order quantity model.

In step 1, described on the next page, the M/M/1/K/K queueing system will be used to obtain probability expressions of the form $P(N_i > K_i - D_i)$. These expressions are obtained as follows:

$$P(N_i > K_i - D_i) = \sum_{n=K_i-D_i+1}^{K_i} P(N_i = n)$$

where:

N_i = Discrete random variable representing the number of units of item i which are broken

K_i = Decision variable representing planned minimum number of units of the item to be owned, including those installed in the repairable equipment

D_i = Number of units of item i which the Korean Air Force wants to have available at all times

The right hand side of the last expression is equal to:

$$1 - \sum_{n=0}^{K_i-D_i} P(N_i = n)$$

using the M/M/1/K/K queue, Allen [Ref. 22: p. 192] gives the following formula for $P(N_i = n)$:

$$P(N_i = n) = \frac{K_i!}{(K_i-n)!}\left(\frac{\alpha_i}{\mu_i}\right)^n P_0$$

where:

$$P_0 = [\sum_{k=0}^{K_i} \frac{K_i!}{(K_i - k)!} (\frac{\alpha_i}{\mu_i})^k]^{-1}$$

In step 2, described in the following section, the expression $P(X_i > S_i)$ is also used. It is obtained using the Poisson distribution:

$$P(X_i = K) = \frac{(D_{ai}L_i)^K e^{-(D_{ai}L_i)}}{K!}$$

where:

X_i = discrete random variable representing attrition demand for item i during a procurement leadtime

D_{ai} = forecasted attrition demand for item i

L_i = forecasted procurement leadtime for item i

We will want S_i such that $P(X_i > S_i)$ is less than a risk value, b_{2i}, which is pre-specified by the user, where $P(X_i > S_i)$, is given by:

$$P(X_i > S_i) = \sum_{k=S_i+1}^{\infty} P(X_i = k)$$

$$= \sum_{k=S_i+1}^{\infty} \frac{(D_{ai}L_i)^k e^{-(D_{ai}L_i)}}{k!}$$

$$= 1 - \sum_{k=0}^{S_i} \frac{(D_{ai}L_i)^k e^{-(D_{ai}L_i)}}{k!}$$

a. Step 1

There are several different objective functions which might be used to help choose the size of the population fot the ith item. The following four subsections describe four different math programs for choosing K_i.

(1) Alternative I

Choose K_i by the following:

$$\min \quad K_i$$

$$\text{subject to} \quad P(N_i > (K_i - D_i)) \leq b_{1i}$$

where:

D_i = Number of units of item i which the Korean Air Force wants to have available at all times

b_{1i} = Parameter chosen by the decision maker

This first alternative formulation contains no explicit budget constraint. However, minimizing K_i for all items is equivalent to minimizing the cost of that portion of the population which is owned to meet the availability goals. Unfortunately, this formulation doesn't identify solutions which exceed the available budget. The next math programming formulation accomplishes this.

(2) *Alternative II*

$$\min \sum_{i=1}^{m} K_i$$

$$\text{subject to} \quad P(N_i > K_i - D_i) \leq b_{1i}, \qquad i = 1,\ldots\ldots,m$$

$$\text{and} \quad \sum_{i=1}^{m} h_i K_i + \sum_{i=1}^{m} a_i[\max(0, K_i - K_{oi})] \leq B$$

where:

h_i = annual holding cost per unit held

B = total budget for one year

m = number of repairable items being considered

K_{oi} = previous planned minimum number of units owned

a_i = unit cost of item i

(3) *Alternative III*

Maximize customer service subject to investment constraint:

$$\min \quad Z = \sum_{i=1}^{m} P(N_i > (K_i - D_i))$$

$$\text{subject to} \sum_{i=1}^{m} h_i K_i + \sum_{i=1}^{m} a_i[\max(0, K_i - K_{oi})] \leq B$$

(4) Alternative IV

Maximize customer service subject to investment constraint (another form):

$$\min \quad Z = \max \; \{P(N_i > (K_i - D_i))\}$$

$$\text{subject to} \sum_{i=1}^{m} h_i K_i + \sum_{i=1}^{m} a_i[\max(0, K_i - K_{oi})] \leq B$$

The choice between these alternate formulations depends on the way the Korean Air Force feels most comfortable with resolving the conflict between budget limitations and customer service. For the numerical computation of this study, we chose alternative II. This choice balanced the need for realism against the time constraints imposed on this research.

b. Step 2

Attrition buy reorder point, $R_i = K_i + S_i$, where S_i is obtained from the following:

$$\min \quad S_i$$

$$\text{subject to} \;\; P(X_i > S_i) \leq b_{2i}$$

where:

X_i = discrete random variable representing attrition demand for item i during a procurement leadtime

b_{2i} = parameter chosen by the decision maker for item i

Using the reorder point R_i, place an attrition buy when the total number of unattrited units (working and failed, installed and uninstalled) reaches or drops below R_i.

c. *Step 3*

Use the Wilson-Harris EOQ model to choose procurement quantity:

$$Q_i^* = \sqrt{\frac{2A_iD_{ai}}{I_iC_i}}$$

where:

A_i = administration and ordering cost for item i

D_{ai} = attrition demand rate for item i

I_i = annual holding cost rate for item i

C_i = unit cost for item i

So the initial buy quantity formula is $R_i + Q_i^* = K_i + S_i + Q_i^*$.

This proposed repairable item inventory control process works as follows. To start the system, purchase $K_i + S_i + Q_i^*$ units. As installed items fails, repair them as soon as possible (i.e. do not use batch repair). When attritions in the repair process reduce the actual population size to $K_i + S_i$, place an attrition buy.

D. SUMMARY

In this chapter, we developed a new inventory model based on the M/M/1/K/K queueing theory and the current repairables management system of the Korean Air Force. In the next chapter, we will compare the current inventory model with the proposed model, in terms of the numerical results of each, using computer computations.

V. COMPARING THE COMPUTATION RESULTS OF THE MODEL

A. INTRODUCTION

In this chapter, we will discuss a specific result for the two models, one is a existing model of the Korean Air Force, the other is a proposed model. The results show only summary of the computer computation and a comparison of the results. The whole computation results are shown in Appendix C.

The purpose of this chapter is to provide a numerical analysis between the proposed model and the current Korean Air Force model. The data used in the computer computation consists of a selection of 8 line items form the data on 50 line items which was obtained from the Korean Air Force. Due to the limited time available for this research, only 8 items were selected for use in the comparison of the models. A selection of high demand and low demand items were chosen. The complete data set is described in Section C of this chapter.

B. MEASURE OF EFFECTIVENESS (MOE)

The following MOEs are all reasonable methodologies for evaluating repairable item inventory models for the Korean Air Force. However, we will concentrate on one MOE for model comparison such as operational availability.

1. Fill Rate

It is computed by taking the total number of units demanded at a base over a fixed period time and dividing that number into the total number of units issued at the time they were are demanded. Thus, fill rate is the percentage of demands that are filled immediately.

2. Operational Rate

Operational rate is the probability that, at any given point in time, there will be no stockouts from base supply (backorders). Operational rate is computed by counting up the length of time (in days) during a year that no backorders existed and dividing this number by 365. This gives us the percentage of time during the year that no backorders were in existence.

Operational rate has an advantage over both the fill rate and mean number of backorders in that it may be directly related to the supply system's effect on operations. However, it has a disadvantage over both the fill rate and mean backorders in that it has a rather bothersome all-or-nothing character.

3. Mean Supply Response Time (MSRT)

MSRT is the mean time it takes for the supply system to respond to the demand for a replacement part or component. It is obtained by taking each stockout that is established during a period of time, observing how many days it takes to satisfy the backorders, adding up all these numbers and dividing the sum by the total number of demands during that period. It is the average time weighted unit short (TWUS).

MSRT is important by itself as an indicator of success of the supply system in meeting response time goals. As a measure, it considers both the likelihood of satisfying demands from stock on hand and the length of the delay in satisfying demands when the system runs out of stock.

4. The Average Number of NORS Aircraft

NORS stands for "not operationally ready because of supply". The average number of NORS aircraft is computed by counting for each aircraft the number of NORS days during the course of a year, adding these numbers up for each aircraft, and finally dividing by 365. Considering that the purpose of a spare parts supply system for the Korean Air Force is to maintain the operational readiness of aircraft, the average number of NORS aircraft would certainly seem to be a reasonable measure of effectiveness. A stockage model attempting to optimize with respect to a NORS measure would require more restrictive assumptions than those optimizing with respect to fill rate, the average backorders, MSRT, or the operational rate. Above all, its lack of "separability" is a cause of major mathematical problems.

Something to note is that the operational sector of the KAF has consistently suggested that the Korean Air Force supply system should be managed in operational terms, not by supply terms. That is, their imminent question has been "How many spares are needed to provide an operational readiness of X percent of the aircraft?".

5. Constraints

The budget available for the investment in spares is either a constraint in all of the models or the objective is to achieve specified performance at the minimum budget. The essence of any inventory control problem is the trade-off between cost and system performance. As mentioned in the beginning of Chapter II, the budget constraint is the major resource constraint for the Korean Air Force.

C. COMPARING THE MODEL RESULTS

1. Data Characteristic

The data used for the model comparison are 8 line items of the 50 line items in the sample data. The whole sample data is shown in Appendices A and B. This data consists of: a) quarterly demand data for 19 quarters; and b) quarterly attrition data for 19 quarters for each item. The demand data was analyzed using Minitab. The mean, standard deviation, variance and squared coefficient of variation were calculated for each item. Since data concerning the failure process for each installed item wasn't available, we estimated the mean item failure rate, α_i by computing mean demand over 5 years, divided by number of aircraft. We estimated the annual item repair rate, μ_i, by dividing actual working hours per year by the average repair time in hours for the item. The current average repair time for each of the 8 items in the sample was obtained from the Korean Air Force [Ref. 23]. These values are shown in the table below. For the purposes of this comparison we assumed that the random variables associated with the failure process and the repair process had exponential distributions.

Table 4. MEAN REPAIR TIME: This table shows the mean active repair times for the 8 sample items

Item number	Mean Repair Time (hours)
1	2.9
2	5.3
3	3.9
4	2.1
5	7.5
6	6.1
7	1.5
8	1.2

The actual data for an item consists of 19 quarterly demand observations during 1984-1988. Items were selected from three different kinds of aircraft, the F-4D/E, F-5A/B and F-16A/B. Appendix B shows the Minitab results for all 50 items in the sample data set.

The data used in this research also included quarterly attrition quantities for 19 quarters. However, for the model comparison, we selected 8 items.[7] The items which were chosen had a variety of annual demands.

2. Comparing the Results

The complete computation results for both models are shown in Appendix C. A summary of these results is shown on the following pages. For the Korean Air Force model, the target operational availability is 90 percent. In the Korean Air Force, this is a fixed level of availability.

During the computational steps, the actual operational availability allows an increase from 90 percent to 93 percent, however the proposed model didn't meet the budget constraint for a 94 percent operational availability. Figure 8 shows the difference of K values; a comparison of the current K values of the Korean Air Force with min K from the proposed model. Figure 9 shows the difference in safety levels for the proposed model and the Korean Air Force model. In the comparison, the attrition protection level[8] of 0.98 is fixed. Appendix C shows the results based on several attrition protection levels between 0.90 and 0.98. SLQ is a safety level for the Korean Air Force model, min S is the attrition safety level for the proposed model. Figure 10 shows the difference in procurement quantities. For the Korean Air Force model, RO is a procurement level, optimal Q is for the proposed model. In the actual difference for the two models, the proposed model has slightly lower procurement quantities than the Korean Air Force model.

3. Description of the Computer Program

For the Korean Air Force repairable item inventory model, we first computed a demand forecast using a trend value to guide our choice of alpha value to be used in an exponential smoothing forecast for the next quarter's demand. When the trend value fell between 0.9 and 1.1, we chose an alpha value of 0.2, otherwise we used an alpha of 0.4. Then the demand forecast was used to calculate the DDR, DRP, RCQ, OSTQ, SLQ and RO. The computational procedure for this current Korean Air Force model is briefly described in the following paragraph. The complete computational results for the Korean Air Force model are shown in Figures 20 to 27, and the whole mathematical

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7 Item numbers for the 8 items chosen from the 50 items are 10, 16, 20, 27, 30, 33, 37 and 46.

8 Attrition protection level is the probability that attrition will not reduce the population of item i below K_i when an attrition reorder is placed when the population drops to the $K_i + S_i$ level.

Operational Availability = 0.90

	1	2	3	4	5	6	7	8
Min K	93	115	234	180	102	239	200	109
Curr K	99	110	195	183	110	199	194	120
Difference	-6	+5	+39	-3	-8	+40	+6	-11

Operational Availability = 0.91

	1	2	3	4	5	6	7	8
Min K	93	115	235	180	102	239	201	109
Curr K	99	110	195	183	110	199	194	120
Difference	-6	+5	+40	-3	-8	+40	+7	-11

Operational Availability = 0.92

	1	2	3	4	5	6	7	8
Min K	93	116	236	181	103	240	202	110
Curr K	99	110	195	183	110	199	194	120
Difference	-6	+6	+41	-2	-7	+41	+8	-10

Operational Availability = 0.93

	1	2	3	4	5	6	7	8
Min K	93	116	237	181	103	241	203	111
Curr K	99	110	195	183	110	199	194	120
Difference	-6	+6	+42	-2	-7	+42	+9	-9

Figure 8. Difference of Total Stock Level

Operational Availability = 0.90   Protection Level = 0.98

	1	2	3	4	5	6	7	8
Min S	1	1	1	2	2	1	2	3
SLQ	2	1	2	1	1	1	3	2
Difference	-1	0	-1	+1	+1	0	-1	+1

Operational Availability = 0.91   Protection Level = 0.98

	1	2	3	4	5	6	7	8
Min S	1	1	1	2	2	1	2	3
SLQ	2	1	2	1	1	1	3	2
Difference	-1	0	-1	+1	+1	0	-1	+1

Operational Availability = 0.92   Protection Level = 0.98

	1	2	3	4	5	6	7	8
Min S	1	1	1	2	2	1	2	3
SLQ	2	1	2	1	1	1	3	2
Difference	-1	0	-1	+1	+1	0	-1	+1

Operational Availability = 0.93   Protection Level = 0.98

	1	2	3	4	5	6	7	8
Min S	1	1	1	2	2	1	2	3
SLQ	2	1	2	1	1	1	3	2
Difference	-1	0	-1	+1	+1	0	-1	+1

Figure 9.   Difference in Safety Levels Between the Two Models

Operational Availability = 0.90

	1	2	3	4	5	6	7	8
Optimal Q	1	1	1	1	1	1	2	2
RO	3	1	2	1	2	1	4	3
Difference	-2	0	-1	0	-1	0	-2	-1

Operational Availability = 0.91

	1	2	3	4	5	6	7	8
Optimal Q	1	1	1	1	1	1	2	2
RO	3	1	2	1	2	1	4	3
Difference	-2	0	-1	0	-1	0	-2	-1

Operational Availability = 0.92

	1	2	3	4	5	6	7	8
Optimal Q	1	1	1	1	1	1	2	2
RO	3	1	2	1	2	1	4	3
Difference	-2	0	-1	0	-1	0	-2	-1

Operational Availability = 0.93

	1	2	3	4	5	6	7	8
Optimal Q	1	1	1	1	1	1	2	2
RO	3	1	2	1	2	1	4	3
Difference	-2	0	-1	0	-1	0	-2	-1

Figure 10. Difference of Optimal Procurement Quantity

process for the Korean Air Force repairable item inventory model is described in Chapter II.

For the DDR, we computed the total demand for each quarter, divided by 365 days. The DRP equals the RTS divided by the sum of RTS, NRTS and COND. The RCQ was computed by multiplying DDR times DRP times RCT. This RCT refers to the repair cycle time allowed for depot level maintenance. For these computations, we used 120 days for RCT because this is the maximum allowed by the Korean Air Force. The OSTQ is computed by multiplying DDR times NDRP times OST. For OST, we used 365 days which is the maximum allowed by the Korean Air Force. The SLQ is computed by finding the square root of 3 times RCQ plus OSTQ. The RO is computed by adding SLQ, RCQ and OSTQ.

For the model comparison, we used two system parameters (SLQ and RO) and the item's current K value. Using the historical demand data obtain from the Korean Air Force, and their current repairable item inventory as described above, the requisition objective (RO) and safety level quantity (SLQ) were computed for each calendar quarter in 1988 (note that the equivalent historical information was not available from the Korean Air Force). The current K value in Figure 8 was obtained by taking the sum of RFI, NRFI and the currently installed population, as of November 1988 (previous historical data was unavailable). The SLQ for model comparison in Figure 9 is the average safety level in 1988. Also, the RO in Figure 10 is the average RO level in 1988.

For the proposed model, we first need to choose b_{1i} for the first constraint set for each item. For b_{1i}, one minus the current target operational availability in the Korean Air Force was used. To obtain the constraining total budget value B, we computed the sum of the current K_{oi} value for each item times its unit cost plus the holding cost for each item, over all 8 items. The rho value ($\frac{\alpha_i}{\mu_i}$) for an item was derived from the average failure rate (α) of that repairable item, divided by its average repair rate (μ).

For the model comparison, a value for the budget constraint had to be obtained. We estimated a value for this variable by summing the following products over all items: K_{oi} times unit cost plus annual holding cost for item i (reminder: K_{oi} is the number of units of item i currently owned by the Korean Air Force).

In step 1, the min K_i values are computed based on two constraints. First, we calculate the probability that N_i is greater than $K_i - D_i$ for an item. The starting value used for K_i is D_i (the size of the currently installed population). For the min K_i in the computer program, we first compute P_0 of the M/M/1/K/K queueing system. And then, we compute $P(N_i = n)$ using P_0. In the $P(N_i = n)$ computation, n equals $K_i - D_i$. If the constraint on $P(N_i > K_i - D_i)$ isn't satisfied by choosing $K_i = D_i$ then we increased K_i by 1. These steps are continued, until $P(N_i > K_i - D_i)$ is less than 0.10. At this time, we took the current n value, and then added D_i to get the min K_i value. After obtaining the min K_i values from the first constraint set for each of the 8 items, the budget constraint is checked. If these K_i values don't satisfy the budget constraint, we go back to the first constraint set and increase the b_{1i} values. In this case, a method for choosing an increased set of b_{1i}'s must be chosen. Two ways exist to do this. The first method is to increase the b_{1i} values simultaneously for all values. The other way of solving this problem is to apply different operational availabilities for each item. In other words, the operational availability chosen would depend on the item characteristics. The first method described above (simultaneous increase of every b_{1i}) was used in this work. If the min K_i satisfies the budget constraint, this is min K_i used the model comparison, in Figure 8. As it turns out, the first set of min K_i values met the budget constraint. So, the min K_i values from the first constraint set gave a feasible solution in the budget constraint. Actually, the budget constraint allowed up to 93 percent operational availability for all 8 items.

For step 2, we use the Poisson probability distribution to get minimum attrition safety levels. Suppose that risk $b_{2i} = 0.1$. This would mean that the attrition protection level is 0.90. Therefore, $1 - b_{2i}$ equals the protection level. For the min S_i, we first calculate probability of $X_i = 0$, and next calculate probability $X_i = 0$ and so on. We sum these individual probabilities up until the cumulative value meets or exceeds the protection level (for the model comparison, we use 0.98). This is the min S_i value for the model comparison in Figure 9.

For step 3, the Wilson-Harris EOQ formula is used. For this formula, a per order ordering cost of 10 percent of the unit cost was used. This is the value which the Korean Air Force currently believes to be in effect [Ref. 1: p. 65]. Similarly, a holding cost rate of 10 percent per year of unit cost was used. The resulting optimal procurement quantities for the model comparison are shown Figure 10. The complete computational results for the proposed model are shown in Figures 28 to 35.

4. Summary of the Results

The proposed model allows for a 93 percent operational availability within the budget constraint. This is an improvement of 3 percent in operational availability with the same budget that was used with the current Korean Air Force model to obtain 90 percent operational availability.

D. SUMMARY

In this chapter, we compared two models based on computer computations using a sample data set. The proposed model has shown an improvement over the current model. However, it doesn't mean the proposed model is better for the Korean Air Force. A tremendous effort would be required to actually implement this model in the Korean Air Force. Furthermore, additional research should be done to explore the performance of the proposed model.

VI. SUMMARY AND CONCLUSION

For this research, there were three major objectives. The first was to review the literature to understand the current Korean Air Force model and other models, such as METRIC, Mod-METRIC, for controlling the stockage decisions in multi-item, multi-echelon inventory systems involving repairable items. The second objective was to develop a new model for the Korean Air Force inventory management system. The last objective was to evaluate this new model by comparing the current Korean Air Force model with this proposed model.

For the first objective, we studied the METRIC family model, ACIM model and U.S Navy model. We then reviewed their basic assumptions and mathematical approach. For the second objective, we reviewed the Korean Air Force inventory management system concept and conditions, and developed a proposed model. In order to accomplish the last objective, sample data from the KAF was used in comparing the Korean Air Force model and proposed model.

Analysis of the sample data revealed that the proposed model yielded some improvement in operational availability and safety level with the same budget. As mentioned in Chapter V, the proposed model requires further research. Currently the research is hard to do because of time constraints and data available from the Korean Air Force. So, additional research should be done to eliminate these shortcomings in the proposed model. Also, for the implementation, we need more data points to obtain better distributions for the demand process and repair time process.

APPENDIX A. SAMPLE DATA LIST 1

A. SAMPLE DATA DEMAND DISTRIBUTION LIST

Table 5. DEMAND DISTRIBUTION LIST

QTR	1	2	3	4	5	6	7	8	9	10
84-1	0	0	0	0	0	0	0	0	0	0
84-2	0	0	0	0	0	0	0	0	0	0
84-3	0	0	0	0	0	0	0	0	0	2
84-4	0	0	0	0	0	0	0	0	0	2
1984 Total	0	0	0	0	0	0	0	0	0	4
85-1	0	0	0	0	0	0	0	0	0	1
85-2	0	0	0	0	0	0	0	0	0	2
85-3	0	0	0	0	0	0	0	0	0	0
85-4	0	0	0	0	0	0	0	0	0	2
1985 Total	0	0	0	0	0	0	0	0	0	5
86-1	0	0	0	2	0	0	0	0	0	0
86-2	0	0	0	0	0	0	0	0	0	2
86-3	0	0	0	1	0	1	0	0	1	0
86-4	0	0	0	0	0	1	0	0	2	3
1986 Total	0	0	0	3	0	2	0	0	3	5
87-1	0	2	0	2	1	0	0	0	5	2
87-2	2	1	0	4	0	1	1	1	7	0
87-3	0	0	0	0	0	0	0	1	2	0
87-4	1	0	1	3	0	2	0	1	2	4
1987 Total	3	3	1	9	1	3	1	3	16	6
88-1	0	2	1	1	0	0	2	0	4	3
88-2	0	1	0	3	0	3	0	1	6	0
88-3	1	0	0	5	1	0	0	1	4	2
1988 Total	1	3	1	9	1	3	2	2	14	5

Table 6. DEMAND DISTRIBUTION LIST

QTR	11	12	13	14	15	16	17	18	19	20
84-1	0	0	0	1	0	6	1	2	1	0
84-2	0	0	0	2	1	1	0	4	7	3
84-3	0	0	0	2	0	0	0	0	2	0
84-4	0	0	0	2	0	2	0	2	5	2
1984 Total	0	0	0	7	1	9	1	8	15	5
85-1	1	0	4	0	1	1	0	8	4	2
85-2	0	0	0	5	0	1	0	0	3	0
85-3	0	0	0	2	0	3	0	0	1	2
85-4	0	1	0	3	1	0	0	0	1	3
1985 Total	1	1	4	10	2	5	0	8	9	7
86-1	0	1	0	4	0	0	2	2	3	4
86-2	0	0	0	1	1	2	0	5	3	0
86-3	0	0	0	3	3	0	0	1	5	3
86-4	0	0	0	2	1	1	0	1	1	2
1986 Total	0	1	0	10	5	3	2	9	12	9
87-1	4	0	0	5	2	1	0	1	0	0
87-2	1	1	0	4	5	0	0	2	4	0
87-3	5	0	1	1	3	1	0	0	1	1
87-4	2	0	0	3	2	1	0	0	2	2
1987 Total	12	1	1	13	12	3	0	3	7	3
88-1	1	0	1	4	3	0	1	0	2	0
88-2	2	1	0	2	2	1	0	1	3	0
88-3	1	0	0	4	0	0	0	0	1	2
1988 Total	4	1	1	10	5	1	1	1	6	2

Table 7. DEMAND DISTRIBUTION LIST

QTR	21	22	23	24	25	26	27	28	29	30
84-1	0	2	0	1	9	4	36	84	4	4
84-2	1	0	0	1	5	5	44	66	7	0
84-3	1	0	0	0	11	4	52	43	1	0
84-4	3	2	4	3	1	0	55	32	7	3
1984 Total	5	4	4	5	26	13	187	225	19	7
85-1	1	4	1	10	0	2	101	71	2	3
85-2	1	1	0	0	10	2	67	59	0	0
85-3	1	1	0	5	5	5	28	50	5	0
85-4	0	1	1	4	4	1	42	25	2	2
1985 Total	3	7	2	19	19	10	238	205	9	5
86-1	2	5	4	5	7	6	61	40	0	3
86-2	4	3	3	1	8	1	17	39	4	1
86-3	0	2	1	1	8	1	95	12	5	0
86-4	1	4	0	4	4	3	47	73	0	5
1986 Total	7	14	8	11	27	11	220	164	9	9
87-1	5	6	2	2	10	2	19	50	11	3
87-2	4	1	0	2	7	7	24	37	7	0
87-3	1	3	0	0	3	0	25	21	4	0
87-4	0	1	7	0	0	4	70	24	13	4
1987 Total	10	11	9	4	20	13	138	132	35	7
88-1	0	5	1	5	9	10	42	31	5	2
88-2	6	2	0	6	9	1	21	18	9	0
88-3	0	3	2	2	5	3	18	23	3	4
1988 Total	6	10	3	13	23	14	81	72	17	6

Table 8. DEMAND DISTRIBUTION LIST

QTR	31	32	33	34	35	36	37	38	39	40
84-1	0	0	0	9	1	2	2	0	12	1
84-2	5	0	1	7	7	1	3	0	21	7
84-3	4	0	2	9	0	1	0	0	6	3
84-4	0	0	1	18	2	9	3	5	2	1
1984 Total	9	0	4	43	10	13	8	5	41	12
85-1	12	0	1	17	10	4	2	1	17	2
85-2	20	3	1	2	26	3	0	1	9	0
85-3	1	0	3	2	32	1	1	0	13	5
85-4	14	0	0	7	25	3	2	2	5	1
1985 Total	47	3	5	28	93	11	5	4	44	8
86-1	17	1	0	4	30	5	2	4	10	0
86-2	25	0	1	2	11	0	5	0	0	13
86-3	0	1	0	9	17	0	5	0	5	7
86-4	21	2	1	0	4	6	0	3	6	6
1986 Total	63	4	2	15	62	11	12	7	21	26
87-1	5	0	0	4	9	3	1	1	2	5
87-2	5	1	2	5	5	3	2	1	2	5
87-3	0	0	2	5	2	1	0	0	7	5
87-4	4	0	0	0	17	7	3	0	4	3
1987 Total	14	1	4	14	33	14	6	2	14	18
88-1	10	0	0	0	0	1	0	0	0	0
88-2	3	0	1	0	10	1	0	0	4	3
88-3	7	0	1	5	4	2	4	0	5	0
1988 Total	20	0	2	5	14	4	4	0	9	3

Table 9. DEMAND DISTRIBUTION LIST

QTR	41	42	43	44	45	46	47	48	49	50
84-1	0	0	1	4	7	14	28	5	3	13
84-2	0	0	0	9	7	0	30	6	3	9
84-3	0	0	0	9	9	0	17	11	9	10
84-4	0	0	0	10	2	11	29	12	3	17
1984 Total	0	0	1	32	25	25	104	34	18	49
85-1	8	1	2	5	1	5	23	8	5	15
85-2	8	1	2	5	1	10	23	8	5	15
85-3	1	7	0	8	4	0	13	13	0	8
85-4	3	3	4	5	2	6	11	7	4	8
1985 Total	20	12	8	23	8	21	70	36	14	46
86-1	4	0	0	10	0	9	7	12	2	20
86-2	7	4	1	13	11	0	19	10	3	0
86-3	1	1	1	7	9	0	18	5	7	6
86-4	4	2	3	5	5	11	6	16	0	16
1986 Total	16	7	5	35	25	20	50	43	12	42
87-1	0	5	0	1	6	9	5	9	0	8
87-2	0	1	1	1	6	7	9	10	6	1
87-3	0	1	0	9	2	0	8	3	3	9
87-4	2	0	0	6	4	13	8	11	0	15
1987 Total	2	7	1	17	18	29	30	33	9	33
88-1	0	0	0	0	5	0	7	11	0	4
88-2	0	4	1	3	2	0	5	4	5	7
88-3	1	0	0	3	1	12	14	7	1	6
1986 Total	1	4	1	6	8	12	26	22	6	17

APPENDIX B. SAMPLE DATA LIST 2

A. SAMPLE DATA DISPOSAL RATE DISTRIBUTION LIST

Table 10. DISPOSAL RATE DISTRIBUTION LIST

QTR	1	2	3	4	5	6	7	8	9	10
84-1	0	0	0	0	0	0	0	0	0	0
84-2	0	0	0	0	0	0	0	0	0	0
84-3	0	0	0	0	0	0	0	0	0	0
84-4	0	0	0	0	0	0	0	0	0	0
85-1	0	0	0	0	0	0	0	0	0	0
85-2	0	0	0	0	0	0	0	0	0	0
85-3	0	0	0	0	0	0	0	0	0	1
85-4	0	0	0	0	0	0	0	0	0	0
86-1	0	0	0	0	0	0	0	0	0	0
86-2	0	0	0	0	0	0	0	0	0	0
86-3	0	0	0	0	0	0	0	0	0	0
86-4	0	0	0	0	0	0	0	0	0	0
87-1	0	0	0	0	0	0	0	0	0	0
87-2	0	0	0	0	0	0	0	0	0	0
87-3	0	0	0	0	0	0	0	0	0	0
87-4	0	0	0	0	0	0	0	0	0	1
88-1	0	0	0	0	0	0	0	0	0	0
88-2	0	0	0	0	0	0	0	0	0	0
88-3	0	0	0	0	0	0	0	0	0	0
P(successful repair)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92

Table 11. DISPOSAL RATE DISTRIBUTION LIST

QTR	11	12	13	14	15	16	17	18	19	20
84-1	0	0	0	0	0	0	0	0	0	0
84-2	0	0	0	0	0	2	0	0	0	0
84-3	0	0	0	0	0	0	0	0	0	0
84-4	0	0	0	0	0	0	0	0	1	0
85-1	0	0	0	0	0	0	0	0	0	0
85-2	0	0	0	0	0	0	0	0	0	0
85-3	0	0	0	0	0	0	0	0	0	0
85-4	0	0	0	1	0	0	0	0	0	0
86-1	0	0	0	1	0	0	0	0	0	0
86-2	0	0	0	0	0	0	0	0	0	0
86-3	0	0	0	0	0	0	0	0	1	0
86-4	0	0	0	0	0	0	0	0	0	0
87-1	0	0	0	0	0	0	0	0	0	0
87-2	0	0	0	0	0	0	0	0	0	0
87-3	0	0	0	0	0	0	0	0	0	0
87-4	0	0	0	1	0	0	0	0	0	1
88-1	0	0	0	1	0	0	0	0	0	0
88-2	0	0	0	0	0	0	0	0	1	0
88-3	0	0	0	0	0	0	0	0	0	0
P(successful repair)	1.00	1.00	1.00	0.92	1.00	0.94	1.00	1.00	0.94	1.00

Table 12. DISPOSAL RATE DISTRIBUTION LIST

QTR	21	22	23	24	25	26	27	28	29	30
84-1	0	0	0	0	1	0	0	0	0	0
84-2	0	0	0	0	1	0	0	2	0	0
84-3	0	0	0	0	0	0	0	0	0	0
84-4	0	0	0	0	0	0	0	0	0	0
85-1	0	0	0	0	0	0	2	0	1	0
85-2	0	0	0	3	0	0	0	1	0	0
85-3	0	0	0	0	1	1	0	0	0	0
85-4	0	0	0	0	0	0	0	0	0	0
86-1	0	0	0	4	0	0	0	0	0	0
86-2	0	0	0	0	0	0	0	0	0	0
86-3	0	0	0	0	0	0	1	0	1	0
86-4	0	0	0	2	0	0	0	0	0	0
87-1	0	0	0	0	0	0	0	0	0	0
87-2	2	0	0	0	1	0	0	1	0	0
87-3	0	0	0	0	0	0	0	0	1	0
87-4	0	0	1	1	0	0	0	0	0	0
88-1	0	0	0	1	0	1	1	1	0	0
88-2	0	0	0	0	0	0	0	0	1	0
88-3	0	0	0	1	0	0	0	0	0	0
P(successful repair)	0.94	1.00	0.96	0.97	0.97	0.97	0.99	0.99	0.96	1.00

Table 13. DISPOSAL RATE DISTRIBUTION LIST

QTR	31	32	33	34	35	36	37	38	39	40
84-1	0	0	0	0	0	0	3	0	0	0
84-2	0	0	0	0	0	0	0	0	2	0
84-3	0	0	0	0	0	0	1	0	0	0
84-4	0	0	0	0	0	0	0	0	0	0
85-1	0	0	0	0	0	0	0	0	1	0
85-2	1	0	0	0	0	0	1	0	0	0
85-3	0	0	1	0	0	0	0	0	0	1
85-4	0	0	0	0	0	0	0	0	0	0
86-1	0	0	0	0	1	0	1	0	0	0
86-2	1	0	0	0	0	0	1	0	0	2
86-3	0	0	0	0	0	0	0	0	0	0
86-4	0	0	0	0	0	0	0	0	0	0
87-1	0	0	0	0	0	0	0	0	0	0
87-2	0	0	0	0	0	0	0	0	0	0
87-3	0	0	0	0	0	0	0	0	1	1
87-4	0	0	0	0	0	0	0	0	0	0
88-1	1	0	0	0	0	0	0	0	0	0
88-2	0	0	0	0	0	0	0	0	0	0
88-3	0	0	0	0	0	0	0	0	1	0
P(successful repair)	0.98	1.00	0.99	1.00	0.99	1.00	0.99	1.00	0.96	0.94

Table 14. DISPOSAL RATE DISTRIBUTION LIST

QTR	41	42	43	44	45	46	47	48	49	50
84-1	0	0	0	0	0	2	0	0	0	1
84-2	0	0	0	0	0	0	1	0	1	0
84-3	0	0	0	0	0	0	0	0	0	0
84-4	0	0	0	1	0	0	0	1	0	0
85-1	0	0	0	0	0	1	0	0	1	0
85-2	0	0	0	0	0	0	2	0	0	0
85-3	0	1	0	0	0	0	0	1	0	0
85-4	0	0	0	0	0	0	0	0	1	0
86-1	0	0	0	0	0	0	0	0	0	1
86-2	0	0	0	1	0	0	0	0	0	0
86-3	0	0	0	2	0	0	0	0	0	0
86-4	0	0	0	0	0	0	0	1	0	0
87-1	0	0	0	0	0	1	0	2	0	0
87-2	0	0	0	0	0	1	0	0	2	0
87-3	0	0	0	0	0	0	0	0	0	0
87-4	0	0	0	0	0	0	1	0	0	1
88-1	0	0	0	0	0	0	0	1	0	0
88-2	0	0	0	0	0	0	0	0	0	0
88-3	0	0	0	0	0	0	0	0	0	0
P(successful repair)	1.00	0.97	1.00	0.97	1.00	0.99	0.99	0.96	0.92	0.98

B. SAMPLE DATA ANALYSIS

Table 15. DEMAND DISTRIBUTION ANALYSIS LIST

No	Mean	Mean²	S.D	Var	C_X^2
1	0.364	0.133	0.674	0.454	3.43
2	0.545	0.297	0.820	0.672	2.26
3	0.182	0.033	0.405	0.164	4.97
4	1.909	3.644	1.700	2.890	0.79
5	1.909	3.644	1.700	2.890	0.79
6	0.727	0.529	1.009	1.018	1.92
7	0.273	0.075	0.647	0.419	5.59
8	0.455	0.207	0.522	0.275	1.32
9	3.091	9.554	2.343	5.489	0.57
10	1.316	1.732	1.293	2.940	0.98
11	0.895	0.801	1.449	2.099	2.62
12	0.211	0.044	0.419	0.176	3.99
13	0.316	0.099	0.946	0.895	8.97
14	2.632	6.927	1.422	2.022	0.29
15	1.316	1.732	1.176	2.055	1.19
16	0.842	0.709	0.834	0.696	0.98
17	0.211	0.045	0.535	0.286	6.36
18	1.526	2.329	2.118	4.486	1.93
19	2.579	6.651	1.805	3.258	0.49
20	1.367	1.869	1.342	1.837	0.98
21	1.632	2.663	1.862	3.467	1.30
22	2.421	5.861	1.742	3.035	0.52
23	1.444	2.085	1.947	3.791	1.82
24	2.737	7.491	2.642	6.967	0.93
25	5.362	31.719	3.609	13.025	0.41

Table 16. DEMAND DISTRIBUTION ANALYSIS LIST

No	Mean	Mean²	S.D	Var	C_X^2
26	3.211	10.311	2.594	6.279	0.65
27	45.470	2067.521	24.880	619.014	0.30
28	42.000	1764.000	20.700	428.490	0.24
29	4.684	21.939	3.667	13.447	0.61
30	1.789	3.201	1.782	3.168	0.99
31	8.050	64.810	7.920	62.726	0.97
32	0.421	0.177	0.838	0.702	5.65
33	0.895	0.801	0.875	0.766	0.96
34	5.530	30.581	5.230	27.353	0.89
35	11.160	124.550	10.420	108.576	0.87
36	2.789	7.779	2.463	6.066	0.78
37	1.526	2.329	1.467	2.236	0.96
38	0.947	0.897	1.508	2.274	2.54
39	6.790	46.104	5.700	32.490	0.70
40	3.684	13.572	3.284	10.785	0.79
41	2.053	4.215	2.838	8.054	1.91
42	1.579	2.493	2.063	4.256	1.71
43	0.842	0.709	1.167	1.362	1.92
44	6.053	36.639	3.353	12.496	0.34
45	4.632	21.455	3.077	9.468	0.44
46	5.630	31.697	5.380	30.112	0.95
47	14.890	221.712	8.720	76.038	0.34
48	8.842	78.181	3.404	11.587	0.15
49	3.105	9.6414	2.622	6.8759	0.71
50	9.420	88.736	5.370	28.837	0.35

```
program ROKAF (input,output);
type
tab10 = array [1..19,1..8] of real;
tab20 = array [1..8] of real;
tab30 = array [1..8,1..19,1..8] of real;
var
chk : boolean;
i,j,k : integer;
in_tab : tab10;
DDR_tab : tab10;
DRP_tab : tab10;
RCQ_tab : tab10;
OSTQ_tab : tab10;
SLQ_tab : tab10;
NO_tab : tab10;
ALP_tab : tab20;
TRND_tab : tab20;
FCST_tab : tab20;
EXP_tab  : tab10;
DIS_tab  : tab10;
TEMP_tab : tab30;

PROCEDURE  title(k:integer);

begin
  case k of
       1 : writeln (' ****  TREND  ANALYSIS    *****');
       2 : writeln (' ****  EXPONENTIAL   SMOOTHING  *****');
       3 : writeln (' ****          DDR         *****');
       4 : writeln (' ****          DRP         *****');
       5 : writeln (' ****          RCQ         *****');
       6 : writeln (' ****          OSTQ        *****');
       7 : writeln (' ****          SLQ         *****');
       8 : writeln (' ****          NO          *****');
    end (case k ) .
end;


PROCEDURE rec (i,j,k:integer;var TEMP_tab :tab30 );
begin
    case k of
     1 : TEMP_tab[k,i,j] := IN_tab [i,j];
     2 : TEMP_tab[k,i,j] := EXP_tab [i,j];
     3 : TEMP_tab[k,i,j] := DDR_tab [i,j];
     4 : TEMP_tab[k,i,j] := DRP_tab [i,j];
     5 : TEMP_tab[k,i,j] := RCQ_tab [i,j];
     6 : TEMP_tab[k,i,j] := OSTQ_tab[i,j];
     7 : TEMP_tab[k,i,j] := SLQ_tab [i,j];
     8 : TEMP_tab[k,i,j] := NO_tab [i,j];
    end (case k)
 end;
```

Figure 11.   Computer programs for the KAF Model

```
(*****  MAIN   PROGRAM  ****)
begin


(*>>>>  DATA INPUT ROUTINE   <<<<*)


writeln ('    DEMAND  DATA !!!  ');
for i := 1 to 19 do
 begin
   writeln (' FOR  D',i);
   for j := 1 to 8 do
   read (in_tab[i,j]);
 end;

writeln ('  DISPOSAL  RATE  !!! ');
for i := 1 to 19 do
 begin
    writeln (' FOR  DR',i);
    for j := 1 to 8 do
    read (DIS_tab [ i,j]);
 end;

(*>>>>  TREND   ANALYSIS <<<<*)

begin
  for i := 1 to 8 do
  begin
    TRND_tab [i] := (((IN_tab[18,i]+IN_tab[19,i])*2)/(IN_tab[16,i]+IN_tab[17,i]+
IN_tab[18,i]
                        + IN_tab[19,i]));
    if (TRND_tab [i] >= 0.9)  and (TRND tab[i] <= 1.1) then
                                      ALP_tab [i] := 0.2
    else
    ALP_tab[i] := 0.4;
  end;
end;

(*>>>>   EXPONENTIAL  SMOOTHING    <<<<*)

 for i := 1 to 8 do
   EXP_tab [1,i] := IN_tab [1,i];
 for i := 2 to 19 do
 begin
   for j := 1 to 8 do
     EXP_tab [i,j] := (ALP_tab [j] * IN_tab [i,j]) + (( 1 - ALP_tab [j])
                        * EXP_tab [i-1,j]);
 end;
 for i := 1 to 8 do
     FCST_tab [i] := (ALP_tab [i] * IN_tab  [19,i]) + ((1 - ALP_tab [i])
                        * EXP_tab [19,i]);

 (*>>>>   DAILY  DEMAND  RATE    <<<<*)

  for i := 1  to 19  do
  begin
     for j := 1 to 8 do
       DDR_tab [ i,j] := IN_tab [ i,j] / 91;
  end;
```

Figure 12.   Computer programs for the KAF Model

```
(*>>>>    DEPOT REPAIR PERCENT    <<<<*)

for i := 1 to 19 do
 begin
   for j := 1 to 8 do
     if DIS_tab [i,j] = 0.0    then DRP_tab [i,j] := 1.0
     else
       begin
       if IN_tab [i,j] = 0 then DRP_tab [i,j] := 0.0
         else
            DRP_tab [i,j ] := DIS_tab [i,j] / IN_tab [i,j];
       end;
     if (DIS_tab [i,j] = 1) and (IN_tab [i,j] = 1) then DRP_tab [i,j] := 0.0;
  end;


(*>>>>    RCQ & OSTQ SLQ RO    <<<<*)
for i := 1 to 19 do
 begin
   for j:= 1 to 8 do
     begin
     RCQ_tab [i,j] := DDR_tab [i,j] * DRP_tab [i,j] * 120;
     OSTQ_tab [i,j] := DDR_tab [i,j] * ( 1 - DRP_tab [i,j]) * 365;
     SLQ_tab [i,j] := sqrt ( 3 * (RCQ_tab [i,j] + OSTQ_tab [i,j]));
     RO_tab [i,j] := SLQ_tab[i,j] + RCQ_tab[i,j] + OSTQ_tab [i,j];
     end;
end;


(*>>>>    PRINT ROUTINE    <<<<*)
  chk := false;
  for k := 1 to 8 do
  begin
   writeln;
   writeln;
   writeln;

     title (k);
     writeln ('  QTR                    1                    2                    3
          4');
     writeln (' ---   --------------   ---------------   ---------------   -
-----------');
     for i := 1 to 19 do
     begin
        write ('  D',i);
        for j := 1 to 4 do
         begin
           rec (i,j,k,TEMP_tab);
           write ('  ',TEMP_tab[k,i,j]);
         end;
        writeln;
     end;
```

Figure 13.   Computer programs for the KAF Model

```
          if k = 1  then
                                                    begin
                                                    writeln;
                                                    writeln;
                                                    write ('  ALP');
                                                    for j := 1 to 4 do
                                                      write (' ',ALP_tab [j]);
                                                     writeln;
                                                    end;
          if k = 2  then
                                                    begin
                                                      writeln;
                                                      writeln;
                                                      write ('  FCT');
                                                      for j := 1 to 4 do
                                                        write (' ',FCST_tab[j]);
                                                      writeln;
                                                    end;

    writeln;
    writeln;
    writeln (' QTR                    5                    6                    7
         8');
    writeln (' ---     -------------   ----------------   ---------------
-----------');
    for i := 1 to 19 do
    begin
         write (' D',i);
         for j := 5 to 8 do
           begin
             rec (i,j,k,TEMP_tab);
             write(' ',TEMP_tab[k,i,j]);

           end;
         writeln;
    end;

             if  k = 1   then
                                                       begin
                                                         writeln;
                                                         writeln;
                                                         write(' ALP');
                                                         for j := 5 to 8 do
                                                           write(' ',ALP_tab[j]);
                                                         writeln;
                                                       end;
             if k = 2 then
                                                       begin
                                                        writeln;
                                                        writeln;
                                                        write(' FCT');
                                                         for j := 5 to  8 do
                                                          write(' ',FCST_tab[j]);
                                                          writeln;
                                                       end;

  end;
end.
```

Figure 14.   Computer programs for the KAF Model

```
program test;
type
  array_a = array [1..8] of real;
  array_K = array [1..8] of integer;
  array_x = array [1..9] of real;
var
  arr_a : array_a;
  arr_K : array_K;
  arr_Kc: array_K;
  arr_D : array_K;
  arr_rho : array_a;
  arr_DL: array_a;
  arr_x : array_x;
  arr_Da : array_a;
  arr_Q  : array_a;
  arr_S : array_K;
  i,total,j,n,item_no,x,q_temp : integer;
  fact,sum,P0,exp_cost,prot_level : real;
  do_again : boolean;

const
  Budget = 19945080;
  IC = 0.1;
  OA = 0.9;

(*>>>>  STEP I  <<<<*)

function get_P0(Kc:integer;rho:real):real;
var
  k : integer;

begin
  fact := 1;
  sum := 0;
  for k := 0 to Kc do
   begin
     for i:= Kc downto Kc-k+1 do
        fact := fact * i*rho;
    { writeln('k= ',k,'  fact= ',fact);}
     sum:= sum + fact;
    { writeln('sum = ',sum);}
     fact := 1;
   end;
  get_P0 := 1/sum;
  writeln('P0 = ',1/sum);
end;
```

Figure 15. Computer programs for the proposed Model

```
procedure initial_n(var arr_n:array_n);
begin
  arr_n[1] := 11670.93*1.1;
  arr_n[2] := 3679.09*1.1;
  arr_n[3] := 5354.00*1.1;
  arr_n[4] := 11001.02*1.1;
  arr_n[5] := 32419.00*1.1;
  arr_n[6] := 7967.05*1.1;
  arr_n[7] := 11869.72*1.1;
  arr_n[8] := 51043.71*1.1;
end;

procedure display_minK(arr_K : array_K);
begin
  writeln('     min K1 = ',arr_K[1]);
  writeln('     min K2 = ',arr_K[2]);
  writeln('     min K3 = ',arr_K[3]);
  writeln('     min K4 = ',arr_K[4]);
  writeln('     min K5 = ',arr_K[5]);
  writeln('     min K6 = ',arr_K[6]);
  writeln('     min K7 = ',arr_K[7]);
  writeln('     min K8 = ',arr_K[8]);
end;

function nth_power(DL : real;power : integer):real;
begin
  if power = 0 then
     nth_power := 1
  else
     nth_power := DL * nth_power(DL,power-1);
end;


function fac(num : integer):integer;
begin
  if num = 0 then
     fac := 1
  else
     fac := num * fac(num-1);
end;


function get_S(DL:real;prob_level:real):integer;
var
  P_sum : real;
  i : integer;

begin
  P_sum := 0.0;
  i := 0;
  repeat
     P_sum := P_sum + nth_power(DL,i)*(exp(-DL))/fac(i);
     i := i + 1;
  until P_sum >= prob_level;
  get_S := i-1;
end;
```

Figure 16. Computer programs for the proposed Model

```
procedure get_DL(var arr_DL : array_n);
begin
   arr_DL[1] := 0.124;
   arr_DL[2] := 0.052;
   arr_DL[3] := 0.154;
   arr_DL[4] := 0.304;
   arr_DL[5] := 0.230;
   arr_DL[6] := 0.056;
   arr_DL[7] := 0.318;
   arr_DL[8] := 0.048;
end;


procedure display_S(arr_S : array_K);
begin
  write('  ',arr_S[1]);
  write('  ',arr_S[2]);
  write('  ',arr_S[3]);
  write('  ',arr_S[4]);
  write('  ',arr_S[5]);
  write('  ',arr_S[6]);
  write('  ',arr_S[7]);
  writeln('  ',arr_S[8]);
end;

procedure get_init(var arr_Kc,arr_D : array_K; var arr_rho : array_n);
begin
   arr_Kc[1] := 99;
   arr_Kc[2] := 110;
   arr_Kc[3] := 195;
   arr_Kc[4] := 183;
   arr_Kc[5] := 110;
   arr_Kc[6] := 199;
   arr_Kc[7] := 194;
   arr_Kc[8] := 120;

   arr_D[1] := 88 ;
   arr_D[2] := 88 ;
   arr_D[3] := 175;
   arr_D[4] := 175;
   arr_D[5] := 88 ;
   arr_D[6] := 175;
   arr_D[7] := 175;
   arr_D[8] := 88 ;

   arr_rho[1] := 0.00668;
   arr_rho[2] := 0.01040;
   arr_rho[3] := 0.00661;
   arr_rho[4] := 0.00370;
   arr_rho[5] := 0.00064;
   arr_rho[6] := 0.00662;
   arr_rho[7] := 0.00529;
   arr_rho[8] := 0.00071;
```

Figure 17. Computer programs for the proposed Model

```
  arr_x[1] := 0.90;
  arr_x[2] := 0.91;
  arr_x[3] := 0.92;
  arr_x[4] := 0.93;
  arr_x[5] := 0.94;
  arr_x[6] := 0.95;
  arr_x[7] := 0.96;
  arr_x[8] := 0.97;
  arr_x[9] := 0.98;

end;


begin
  initial_a(arr_a);
  get_init(arr_Kc,arr_D,arr_rho);

  repeat
  do_again := false;
  item_no := 0;
  exp_cost := 0.0;

  repeat
  item_no := item_no + 1;
  P0 := get_P0(arr_Kc[item_no],arr_rho[item_no]);
  fact := 1;
  sum := 0;
  n := 0;
  repeat
     for i:= arr_Kc[item_no] downto arr_Kc[item_no]-n+1 do
        fact := fact * i/arr_rho[item_no];
     fact := fact*P0;                    (necessary to comment)
     write('   n = ',n);
     sum:= sum + fact;
     writeln('                   sum = ',sum);
     fact := 1;
     n := n + 1;
  until (1 - sum) <= (1 - (A));
  writeln('min K = ',arr_D[item_no]+n-1);
  arr_K[item_no] := arr_D[item_no] + n -1;
  exp_cost := exp_cost + arr_a[item_no]*(arr_D[item_no]+n-1);
  until item_no = 8;
  if exp_cost <= Budget then
     display_minK(arr_K)
  else
       do_again := true;
  until not do_again;

(*>>>>   STEP II   <<<<*)

  writeln(' prot_level         S1 S2 S3 S4 S5 S6 S7 S8');
  writeln(' ----------         -----------------------');
  for x := 1 to 9 do
  begin
```

Figure 18.   Computer programs for the proposed Model

```
 write('  ',arr_x[x]);
 item_no := 0;
 get_DL(arr_DL);
 repeat
    item_no := item_no + 1;
    arr_S[item_no] := get_S(arr_DL[item_no],arr_x[x]);
 until item_no = 8;
 display_S(arr_S);
 end;


(*>>>>   STEP III <<<<*)

 arr_Da[1] := 0.2;
 arr_Da[2] := 0.2;
 arr_Da[3] := 0.2;
 arr_Da[4] := 0.4;
 arr_Da[5] := 0.2;
 arr_Da[6] := 0.2;
 arr_Da[7] := 0.6;
 arr_Da[8] := 0.6;
 writeln;
 writeln;
 writeln ('*>>>>  OPTIMAL PROCUREMENT QUANTITY  <<<<*');
 for x := 1 to 8 do
 begin
   arr_Q [x] := sqrt ((2* (0.1 * (arr_a[x]/1.1))* arr_Da [x])/(1C * (arr_a[x]/1.1)));
   write ('      Q',x);
   writeln(' = ',arr_Q[x]);
 end;
 writeln;
 writeln;
 writeln ('             K        S       Q        TOTAL');
 writeln ('            ---      ---     ---       -----');
 for x := 1 to 8 do
   begin
   if arr_Q[x] <= 2 then Q_temp :=2;
   if arr_Q[x] <= 1 then q_temp :=1;
   total := arr_K[x] + arr_S[x] + q_temp;
   write('   ',x);
   if x = 1 then write(' ');
   write('       ',arr_k[x]);
   write('         ',arr_S[x]);
   write('        ',q_temp);
   if x = 1  then write (' ');
   write('          ',total);
   writeln;
   end;
end.
```

Figure 19. Computer programs for the proposed Model

```
****  TREND  ANALYSIS   *****
```

QTR	1	2	3	4
D1	4.0000000000E+00	2.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D2	0.0000000000E+00	3.0000000000E+00	0.0000000000E+00	3.0000000000E+00
D3	0.0000000000E+00	0.0000000000E+00	2.0000000000E+00	0.0000000000E+00
D4	3.0000000000E+00	3.0000000000E+00	2.0000000000E+00	2.0000000000E+00
D5	3.0000000000E+00	2.0000000000E+00	1.0000000000E+00	2.0000000000E+00
D6	0.0000000000E+00	0.0000000000E+00	2.0000000000E+00	0.0000000000E+00
D7	0.0000000000E+00	1.0000000000E+00	0.0000000000E+00	2.0000000000E+00
D8	2.0000000000E+00	2.0000000000E+00	2.0000000000E+00	3.0000000000E+00
D9	3.0000000000E+00	2.0000000000E+00	0.0000000000E+00	4.0000000000E+00
D10	1.0000000000E+00	0.0000000000E+00	2.0000000000E+00	0.0000000000E+00
D11	0.0000000000E+00	5.0000000000E+00	0.0000000000E+00	3.0000000000E+00
D12	5.0000000000E+00	0.0000000000E+00	3.0000000000E+00	2.0000000000E+00
D13	3.0000000000E+00	1.0000000000E+00	2.0000000000E+00	0.0000000000E+00
D14	0.0000000000E+00	2.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D15	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	1.0000000000E+00
D16	4.0000000000E+00	3.0000000000E+00	4.0000000000E+00	2.0000000000E+00
D17	2.0000000000E+00	0.0000000000E+00	3.0000000000E+00	0.0000000000E+00
D18	0.0000000000E+00	3.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D19	4.0000000000E+00	0.0000000000E+00	2.0000000000E+00	2.0000000000E+00
ALP	4.0000000000E-01	2.0000000000E-01	4.0000000000E-01	2.0000000000E-01

QTR	5	6	7	8
D1	0.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.4000000000E+01
D2	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	0.0000000000E+00
D3	2.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D4	1.0000000000E+00	2.0000000000E+00	3.0000000000E+00	1.1000000000E+01
D5	1.0000000000E+00	1.0000000000E+00	1.0000000000E+01	5.0000000000E+00
D6	1.0000000000E+00	1.0000000000E+00	0.0000000000E+00	1.0000000000E+01
D7	3.0000000000E+00	3.0000000000E+00	5.0000000000E+00	0.0000000000E+00
D8	0.0000000000E+00	0.0000000000E+00	4.0000000000E+00	6.0000000000E+00
D9	0.0000000000E+00	0.0000000000E+00	5.0000000000E+00	9.0000000000E+00
D10	1.0000000000E+00	2.0000000000E+00	1.0000000000E+00	0.0000000000E+00
D11	0.0000000000E+00	0.0000000000E+00	1.0000000000E+00	0.0000000000E+00
D12	1.0000000000E+00	1.0000000000E+00	4.0000000000E+00	1.1000000000E+01
D13	0.0000000000E+00	1.0000000000E+00	2.0000000000E+00	9.0000000000E+00
D14	2.0000000000E+00	0.0000000000E+00	2.0000000000E+00	7.0000000000E+00
D15	2.0000000000E+00	1.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D16	0.0000000000E+00	1.0000000000E+00	0.0000000000E+00	1.3000000000E+01
D17	0.0000000000E+00	0.0000000000E+00	5.0000000000E+00	0.0000000000E+00
D18	1.0000000000E+00	1.0000000000E+00	6.0000000000E+00	0.0000000000E+00
D19	1.0000000000E+00	0.0000000000E+00	2.0000000000E+00	1.2000000000E+01
ALP	4.0000000000E-01	2.0000000000E-01	4.0000000000E-01	2.0000000000E-01

Figure 20. Computational Results for the KAF Model

**** EXPONENTIAL SMOOTHING *****

QTR	1	2	3	4
D1	4.0000000000E+00	2.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D2	2.4000000000E+00	2.2000000000E+00	0.0000000000E+00	8.0000000000E-01
D3	1.4400000000E+00	1.7600000000E+00	8.0000000000E-01	4.0000000000E-01
D4	2.0640000000E+00	2.0000000000E+00	1.2000000000E+00	7.8400000000E-01
D5	2.4304000000E+00	2.0064000000E+00	1.1600000000E+00	1.0272000000E+00
D6	1.4630400000E+00	1.6051200000E+00	1.5000000000E+00	8.2176000000E-01
D7	8.7702400000E-01	1.4040960000E+00	9.0040000000E-01	1.0574080000E+00
D8	1.3266944000E+00	1.5072768000E+00	1.3402000000E+00	1.4459264000E+00
D9	1.9960166400E+00	1.6690214400E+00	8.0417200000E-01	1.9567411200E+00
D10	1.5976099040E+00	1.3350571520E+00	1.2025036000E+00	1.5653928960E+00
D11	9.5056599040E-01	2.0606857216E+00	7.6950220000E-01	1.0523143168E+00
D12	2.5751355942E+00	1.6549485773E+00	1.6617013240E+00	1.8818514534E+00
D13	2.7450037565E+00	1.5239588610E+00	1.7970207949E+00	1.5054811620E+00
D14	1.6470502539E+00	1.6191670095E+00	1.0702124769E+00	1.2043849302E+00
D15	8.8823015235E-01	1.2953336716E+00	6.4692748016E-01	1.1635079442E+00
D16	2.1929300914E+00	1.5362669373E+00	1.9001564917E+00	1.3308063553E+00
D17	2.1157620540E+00	1.3090135498E+00	2.3920938950E+00	1.0646450843E+00
D18	1.2694577129E+00	1.6472108398E+00	1.4357363370E+00	8.5171606741E-01
D19	2.3616746277E+00	1.3177686719E+00	1.6614410022E+00	1.0813720539E+00
FCT	3.0170047766E+00	1.0542149375E+00	1.7960650013E+00	1.2650902031E+00

QTR	5	6	7	8
D1	0.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.4000000000E+01
D2	4.0000000000E-01	1.0000000000E+00	1.0000000000E+00	1.1200000000E+01
D3	1.0400000000E+00	8.0000000000E-01	6.0000000000E-01	8.9600000000E+00
D4	1.0240000000E+00	1.0400000000E+00	1.5600000000E+00	9.3600000000E+00
D5	1.0144000000E+00	1.0320000000E+00	4.9360000000E+00	8.4944000000E+00
D6	1.0006400000E+00	1.0256000000E+00	2.9616000000E+00	8.7955200000E+00
D7	1.0051040000E+00	1.4204800000E+00	3.7769600000E+00	7.0364160000E+00
D8	1.0031104000E+00	1.1363840000E+00	3.0661760000E+00	6.8291328000E+00
D9	6.4906624000E-01	9.0910720000E-01	4.3197056000E+00	7.2633062400E+00
D10	7.0991974400E-01	1.1272057600E+00	2.9918233600E+00	5.8106449920E+00
D11	4.7395104640E-01	9.0192860000E-01	2.1950940160E+00	4.6485159936E+00
D12	6.0437110784E-01	9.2146288640E-01	2.9170564096E+00	5.9188127949E+00
D13	4.1062266470E-01	9.3717030912E-01	2.5502338458E+00	6.5350502359E+00
D14	1.0463735900E+00	7.4973624730E-01	2.3301403075E+00	6.6280401887E+00
D15	1.4278241593E+00	7.9970099784E-01	1.3980841845E+00	5.3024321510E+00
D16	8.5669419557E-01	8.3983119827E-01	8.3885051068E-01	6.8419457208E+00
D17	5.1401669734E-01	6.7106495862E-01	2.5033103064E+00	5.4735565766E+00
D18	7.0841001041E-01	7.3749196689E-01	3.9019061838E+00	4.3788452613E+00
D19	8.2504601104E-01	5.8999357351E-01	3.1411917103E+00	5.9030762090E+00
FCT	8.9502768662E-01	4.7199405001E-01	2.6047150262E+00	7.1224609677E+00

Figure 21. Computational Results for the KAF Model

**** DDK *****

QTR	1	2	3	4
D1	1.0958904110E-02	5.4794520548E-03	0.0000000000E+00	0.0000000000E+00
D2	0.0000000000E+00	8.2191780822E-03	0.0000000000E+00	8.2191780822E-03
D3	0.0000000000E+00	0.0000000000E+00	5.4794520548E-03	0.0000000000E+00
D4	8.2191780822E-03	8.2191780822E-03	5.4794520548E-03	5.4794520548E-03
D5	8.2191780822E-03	5.4794520548E-03	2.7397260274E-03	5.4794520548E-03
D6	0.0000000000E+00	0.0000000000E+00	5.4794520548E-03	0.0000000000E+00
D7	0.0000000000E+00	2.7397260274E-03	0.0000000000E+00	5.4794520548E-03
D8	5.4794520548E-03	5.4794520548E-03	5.4794520548E-03	8.2191780822E-03
D9	8.2191780822E-03	5.4794520548E-03	0.0000000000E+00	1.0958904110E-02
D10	2.7397260274E-03	0.0000000000E+00	5.4794520548E-03	0.0000000000E+00
D11	0.0000000000E+00	1.3698630137E-02	0.0000000000E+00	8.2191780822E-03
D12	1.3698630137E-02	0.0000000000E+00	8.2191780822E-03	5.4794520548E-03
D13	8.2191780822E-03	2.7397260274E-03	5.4794520548E-03	0.0000000000E+00
D14	0.0000000000E+00	5.4794520548E-03	0.0000000000E+00	0.0000000000E+00
D15	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	2.7397260274E-03
D16	1.0958904110E-02	8.2191780822E-03	1.0958904110E-02	5.4794520548E-03
D17	5.4794520548E-03	0.0000000000E+00	8.2191780822E-03	0.0000000000E+00
D18	0.0000000000E+00	8.2191780822E-03	0.0000000000E+00	0.0000000000E+00
D19	1.0958904110E-02	0.0000000000E+00	5.4794520548E-03	5.4794520548E-03

QTR	5	6	7	8
D1	0.0000000000E+00	2.7397260274E-03	2.7397260274E-03	3.8356164384E-02
D2	2.7397260274E-03	2.7397260274E-03	2.7397260274E-03	0.0000000000E+00
D3	5.4794520548E-03	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D4	2.7397260274E-03	5.4794520548E-03	8.2191780822E-03	3.0136986301E-02
D5	2.7397260274E-03	2.7397260274E-03	2.7397260274E-02	1.3698630137E-02
D6	2.7397260274E-03	2.7397260274E-03	0.0000000000E+00	2.7397260274E-02
D7	8.2191780822E-03	8.2191780822E-03	1.3698630137E-02	0.0000000000E+00
D8	0.0000000000E+00	0.0000000000E+00	1.0958904110E-02	1.6438356164E-02
D9	0.0000000000E+00	0.0000000000E+00	1.3698630137E-02	2.4657534247E-02
D10	2.7397260274E-03	5.4794520548E-03	2.7397260274E-03	0.0000000000E+00
D11	0.0000000000E+00	0.0000000000E+00	2.7397260274E-03	0.0000000000E+00
D12	2.7397260274E-03	2.7397260274E-03	1.0958904110E-02	3.0136986301E-02
D13	0.0000000000E+00	2.7397260274E-03	5.4794520548E-03	2.4657534247E-02
D14	5.4794520548E-03	0.0000000000E+00	5.4794520548E-03	1.9178082192E-02
D15	5.4794520548E-03	2.7397260274E-03	0.0000000000E+00	0.0000000000E+00
D16	0.0000000000E+00	2.7397260274E-03	0.0000000000E+00	3.5616438356E-02
D17	0.0000000000E+00	0.0000000000E+00	1.3698630137E-02	0.0000000000E+00
D18	2.7397260274E-03	2.7397260274E-03	1.6438356164E-02	0.0000000000E+00
D19	2.7397260274E-03	0.0000000000E+00	5.4794520548E-03	3.2876712329E-02

Figure 22. Computational Results for the KAF Model

**** DIP ****

OTR	1	2	3	4
D1	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D2	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	3.3333333333E-01
D3	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D4	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D5	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D6	1.0000000000E+00	1.0000000000E+00	5.0000000000E-01	1.0000000000E+00
D7	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D8	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D9	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	2.5000000000E-01
D10	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D11	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D12	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D13	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D14	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D15	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D16	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D17	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D18	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D19	2.5000000000E-01	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00

OTR	5	6	7	8
D1	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D2	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D3	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D4	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	9.0909090909E-02
D5	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D6	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D7	1.0000000000E+00	3.3333333333E-01	2.0000000000E-01	1.0000000000E+00
D8	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D9	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D10	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D11	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D12	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	9.0909090909E-02
D13	1.0000000000E+00	1.0000000000E+00	5.0000000000E-01	1.1111111111E-01
D14	5.0000000000E-01	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D15	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D16	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D17	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D18	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00
D19	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00	1.0000000000E+00

Figure 23. Computational Results for the KAF Model

**** BCQ *****

QTR	1	2	3	4
D1	1.3150684931E+00	6.5753424657E-01	0.0000000000E+00	0.0000000000E+00
D2	0.0000000000E+00	9.8630136986E-01	0.0000000000E+00	3.2876712329E-01
D3	0.0000000000E+00	0.0000000000E+00	6.5753424657E-01	0.0000000000E+00
D4	9.8630136986E-01	9.8630136986E-01	6.5753424657E-01	6.5753424657E-01
D5	9.8630136986E-01	6.5753424657E-01	3.2876712329E-01	6.5753424657E-01
D6	0.0000000000E+00	0.0000000000E+00	3.2876712329E-01	0.0000000000E+00
D7	0.0000000000E+00	3.2876712329E-01	0.0000000000E+00	6.5753424657E-01
D8	6.5753424657E-01	6.5753424657E-01	6.5753424657E-01	9.8630136986E-01
D9	9.8630136986E-01	6.5753424657E-01	0.0000000000E+00	3.2876712329E-01
D10	3.2876712329E-01	0.0000000000E+00	6.5753424657E-01	0.0000000000E+00
D11	0.0000000000E+00	1.6438356164E+00	0.0000000000E+00	9.8630136986E-01
D12	1.6438356164E+00	0.0000000000E+00	9.8630136986E-01	6.5753424657E-01
D13	9.8630136986E-01	3.2876712329E-01	6.5753424657E-01	0.0000000000E+00
D14	0.0000000000E+00	6.5753424657E-01	0.0000000000E+00	0.0000000000E+00
D15	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	3.2876712329E-01
D16	1.3150684931E+00	9.8630136986E-01	1.3150684931E+00	6.5753424657E-01
D17	6.5753424657E-01	0.0000000000E+00	9.8630136986E-01	0.0000000000E+00
D18	0.0000000000E+00	9.8630136986E-01	0.0000000000E+00	0.0000000000E+00
D19	3.2876712329E-01	0.0000000000E+00	6.5753424657E-01	6.5753424657E-01

QTR	5	6	7	8
D1	0.0000000000E+00	3.2876712329E-01	3.2876712329E-01	4.6027397260E+00
D2	3.2876712329E-01	3.2876712329E-01	3.2876712329E-01	0.0000000000E+00
D3	6.5753424657E-01	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D4	3.2876712329E-01	6.5753424657E-01	9.8630136986E-01	3.2876712329E-01
D5	3.2876712329E-01	3.2876712329E-01	3.2876712329E+00	1.6438356164E+00
D6	3.2876712329E-01	3.2876712329E-01	0.0000000000E+00	3.2876712329E+00
D7	9.8630136986E-01	3.2876712329E-01	3.2876712329E-01	0.0000000000E+00
D8	0.0000000000E+00	0.0000000000E+00	1.3150684931E+00	1.9726027397E+00
D9	0.0000000000E+00	0.0000000000E+00	1.6438356164E+00	2.9589041096E+00
D10	3.2876712329E-01	6.5753424657E-01	3.2876712329E-01	0.0000000000E+00
D11	0.0000000000E+00	0.0000000000E+00	3.2876712329E-01	0.0000000000E+00
D12	3.2876712329E-01	3.2876712329E-01	1.3150684931E+00	3.2876712329E-01
D13	0.0000000000E+00	3.2876712329E-01	3.2876712329E-01	3.2876712329E-01
D14	3.2876712329E-01	0.0000000000E+00	6.5753424657E-01	2.3013698630E+00
D15	6.5753424657E-01	3.2876712329E-01	0.0000000000E+00	0.0000000000E+00
D16	0.0000000000E+00	3.2876712329E-01	0.0000000000E+00	4.2739726027E+00
D17	0.0000000000E+00	0.0000000000E+00	1.6438356164E+00	0.0000000000E+00
D18	3.2876712329E-01	3.2876712329E-01	1.9726027397E+00	0.0000000000E+00
D19	3.2876712329E-01	0.0000000000E+00	6.5753424657E-01	3.9452054794E+00

Figure 24. Computational Results for the KAF Model

```
****          USTO          *****
```

QTR	1	2	3	4
D1	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D2	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	2.0000000000E+00
D3	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D4	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D5	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D6	0.0000000000E+00	0.0000000000E+00	1.0000000000E+00	0.0000000000E+00
D7	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D8	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D9	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	3.0000000000E+00
D10	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D11	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D12	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D13	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D14	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D15	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D16	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D17	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D18	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D19	3.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00

QTR	5	6	7	8
D1	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D2	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D3	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D4	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	1.0000000000E+01
D5	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D6	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D7	0.0000000000E+00	2.0000000000E+00	4.0000000000E+00	0.0000000000E+00
D8	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D9	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D10	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D11	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D12	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	1.0000000000E+01
D13	0.0000000000E+00	0.0000000000E+00	1.0000000000E+00	8.0000000000E+00
D14	1.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D15	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D16	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D17	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D18	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D19	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00

Figure 25. Computational Results for the KAF Model

**** SLQ *****

QTR	1	2	3	4
D1	1.9862541326E+00	1.4044937664E+00	0.0000000000E+00	0.0000000000E+00
D2	0.0000000000E+00	1.7201465372E+00	0.0000000000E+00	2.6431612455E+00
D3	0.0000000000E+00	0.0000000000E+00	1.4044937664E+00	0.0000000000E+00
D4	1.7201465372E+00	1.7201465372E+00	1.4044937664E+00	1.4044937664E+00
D5	1.7201465372E+00	1.4044937664E+00	9.9312706632E-01	1.4044937664E+00
D6	0.0000000000E+00	0.0000000000E+00	1.9965724054E+00	0.0000000000E+00
D7	0.0000000000E+00	9.9312706632E-01	0.0000000000E+00	1.4044937664E+00
D8	1.4044937664E+00	1.4044937664E+00	1.4044937664E+00	1.7201465372E+00
D9	1.7201465372E+00	1.4044937664E+00	0.0000000000E+00	3.1601109743E+00
D10	9.9312706632E-01	0.0000000000E+00	1.4044937664E+00	0.0000000000E+00
D11	0.0000000000E+00	2.2206996306E+00	0.0000000000E+00	1.7201465372E+00
D12	2.2206996306E+00	0.0000000000E+00	1.7201465372E+00	1.4044937664E+00
D13	1.7201465372E+00	9.9312706632E-01	1.4044937664E+00	0.0000000000E+00
D14	0.0000000000E+00	1.4044937664E+00	0.0000000000E+00	0.0000000000E+00
D15	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	9.9312706632E-01
D16	1.9862541326E+00	1.7201465372E+00	1.9862541326E+00	1.4044937664E+00
D17	1.4044937664E+00	0.0000000000E+00	1.7201465372E+00	0.0000000000E+00
D18	0.0000000000E+00	1.7201465372E+00	0.0000000000E+00	0.0000000000E+00
D19	3.1601109743E+00	0.0000000000E+00	1.4044937664E+00	1.4044937664E+00

QTR	5	6	7	8
D1	0.0000000000E+00	9.9312706632E-01	9.9312706632E-01	3.7159412237E+00
D2	9.9312706632E-01	9.9312706632E-01	9.9312706632E-01	0.0000000000E+00
D3	1.4044937664E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D4	9.9312706632E-01	1.4044937664E+00	1.7201465372E+00	5.5665340536E+00
D5	9.9312706632E-01	9.9312706632E-01	3.1405435355E+00	2.2206996306E+00
D6	9.9312706632E-01	9.9312706632E-01	0.0000000000E+00	3.1405435355E+00
D7	1.7201465372E+00	2.6431612455E+00	3.6036511166E+00	0.0000000000E+00
D8	0.0000000000E+00	0.0000000000E+00	1.9862541326E+00	2.4326545622E+00
D9	0.0000000000E+00	0.0000000000E+00	2.2206996306E+00	2.9793011990E+00
D10	9.9312706632E-01	1.4044937664E+00	9.9312706632E-01	0.0000000000E+00
D11	0.0000000000E+00	0.0000000000E+00	9.9312706632E-01	0.0000000000E+00
D12	9.9312706632E-01	9.9312706632E-01	1.9862541326E+00	5.5665340536E+00
D13	0.0000000000E+00	9.9312706632E-01	1.9965724054E+00	4.9986299193E+00
D14	1.9965724054E+00	0.0000000000E+00	1.4044937664E+00	2.6275672378E+00
D15	1.4044937664E+00	9.9312706632E-01	0.0000000000E+00	0.0000000000E+00
D16	0.0000000000E+00	9.9312706632E-01	0.0000000000E+00	3.5007705607E+00
D17	0.0000000000E+00	0.0000000000E+00	2.2206996306E+00	0.0000000000E+00
D18	9.9312706632E-01	9.9312706632E-01	2.4326545622E+00	0.0000000000E+00
D19	9.9312706632E-01	0.0000000000E+00	1.4044937664E+00	3.4402930745E+00

Figure 26. Computational Results for the KAF Model

**** RU *****

GTR	1	2	3	4
D1	3.3013226258E+00	2.0620280129E+00	0.0000000000E+00	0.0000000000E+00
D2	0.0000000000E+00	2.7064179071E+00	0.0000000000E+00	4.9719203608E+00
D3	0.0000000000E+00	0.0000000000E+00	2.0620280129E+00	0.0000000000E+00
D4	2.7064179071E+00	2.7064179071E+00	2.0620280129E+00	2.0620280129E+00
D5	2.7064179071E+00	2.0620280129E+00	1.3218941096E+00	2.0620280129E+00
D6	0.0000000000E+00	0.0000000000E+00	3.3253395206E+00	0.0000000000E+00
D7	0.0000000000E+00	1.3218941896E+00	0.0000000000E+00	2.0620280129E+00
D8	2.0620280129E+00	2.0620280129E+00	2.0620280129E+00	2.7064179071E+00
D9	2.7064179071E+00	2.0620280129E+00	0.0000000000E+00	6.4888780976E+00
D10	1.3218941896E+00	0.0000000000E+00	2.0620280129E+00	0.0000000000E+00
D11	0.0000000000E+00	3.8645352470E+00	0.0000000000E+00	2.7064179071E+00
D12	3.8645352470E+00	0.0000000000E+00	2.7064179071E+00	2.0620280129E+00
D13	2.7064179071E+00	1.3218941896E+00	2.0620280129E+00	0.0000000000E+00
D14	0.0000000000E+00	2.0620280129E+00	0.0000000000E+00	0.0000000000E+00
D15	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00	1.3218941896E+00
D16	3.3013226258E+00	2.7064179071E+00	3.3013226258E+00	2.0620280129E+00
D17	2.0620280129E+00	0.0000000000E+00	2.7064179071E+00	0.0000000000E+00
D18	0.0000000000E+00	2.7064179071E+00	0.0000000000E+00	0.0000000000E+00
D19	6.4888780976E+00	0.0000000000E+00	2.0620280129E+00	2.0620280129E+00

GTR	5	6	7	8
D1	0.0000000000E+00	1.3218941096E+00	1.3218941896E+00	8.3106809197E+00
D2	1.3218941896E+00	1.3218941896E+00	1.3218941896E+00	0.0000000000E+00
D3	2.0620280129E+00	0.0000000000E+00	0.0000000000E+00	0.0000000000E+00
D4	1.3218941896E+00	2.0620280129E+00	2.7064179071E+00	1.5895301177E+01
D5	1.3218941896E+00	1.3218941896E+00	6.4282147684E+00	3.8645352470E+00
D6	1.3218941896E+00	1.3218941896E+00	0.0000000000E+00	6.4282147684E+00
D7	2.7064179071E+00	4.9719203608E+00	7.9324182390E+00	0.0000000000E+00
D8	0.0000000000E+00	0.0000000000E+00	3.3013226258E+00	4.4052573020E+00
D9	0.0000000000E+00	0.0000000000E+00	3.8645352470E+00	5.9302853085E+00
D10	1.3218941896E+00	2.0620280129E+00	1.3218941896E+00	0.0000000000E+00
D11	0.0000000000E+00	0.0000000000E+00	1.3218941896E+00	0.0000000000E+00
D12	1.3218941896E+00	1.3218941896E+00	3.3013226258E+00	1.5895301177E+01
D13	0.0000000000E+00	1.3218941896E+00	3.3253395206E+00	1.3327397073E+01
D14	3.3253395206E+00	0.0000000000E+00	2.0620280129E+00	4.9209371008E+00
D15	2.0620280129E+00	1.3218941896E+00	0.0000000000E+00	0.0000000000E+00
D16	0.0000000000E+00	1.3218941896E+00	0.0000000000E+00	7.8547431634E+00
D17	0.0000000000E+00	0.0000000000E+00	3.8645352470E+00	0.0000000000E+00
D18	1.3218941896E+00	1.3218941896E+00	4.4052573020E+00	0.0000000000E+00
D19	1.3218941896E+00	0.0000000000E+00	2.0620280129E+00	7.3054985539E+00

Figure 27. Computational Results for the KAF Model

```
P=  3.5010067031E-01
    n = 0                    sum =  3.5010067031E-01
    n = 1                    sum =  5.0227304772E-01
    n = 2                    sum =  7.3100969233E-01
    n = 3                    sum =  0.3232045021E-01
    n = 4                    sum =  0.9537030326E-01
    n = 5                    sum =  9.3530974000E-01
min K = 93
PO =  1.5041756040E-02
    n = 0                    sum =  1.5041756046E-02
    n = 1                    sum =  3.3964724062E-02
    n = 2                    sum =  5.4509922525E-02
    n = 3                    sum =  7.7504165228E-02
    n = 4                    sum =  1.0326229531E-01
    n = 5                    sum =  1.3156906591E-01
    n = 0                    sum =  1.6240173300E-01
    n = 7                    sum =  1.9591600045E-01
    n = 0                    sum =  2.3173000431E-01
    n = 9                    sum =  2.6972313976E-01
    n = 10                    sum =  3.0963020092E-01
    n = 11                    sum =  3.5113372404E-01
    n = 12                    sum =  3.9306566005E-01
    n = 13                    sum =  4.3711005003E-01
    n = 14                    sum =  4.0135370105E-01
    n = 15                    sum =  5.2521905503E-01
    n = 16                    sum =  5.6055002556E-01
    n = 17                    sum =  6.1092620237E-01
    n = 10                    sum =  6.5190470290E-01
    n = 19                    sum =  6.9111293237E-01
    n = 20                    sum =  7.2021960065E-01
    n = 21                    sum =  7 6295144217E-01
    n = 22                    sum =  7.9509923460E-01
    n = 23                    sum =  0.2452009430E-01
    n = 24                    sum =  8.5114191200E-01
    n = 25                    sum =  0.7495110199E-01
    n = 26                    sum =  0.9590004179E-01
    n = 27                    sum =  9.1430607739E-01
min K = 115
PO =  9.0010479659E-05
    n = 0                    sum =  0.0010479659E-05
    n = 1                    sum =  2.0146903907E-04
    n = 2                    sum =  3.4695319211E-01
    n = 3                    sum =  5.3255059361E-04
    n = 4                    sum =  7.6003596791E-04
    n = 5                    sum =  1.0654743502E-03
    n = 6                    sum =  1.4303518707E-03
    n = 7                    sum =  1.9055398102E-03
    n = 8                    sum =  2.4053453964E-03
    n = 9                    sum =  3.2020333509E-03
    n = 10                    sum =  4.0031725234E-03
    n = 11                    sum =  5.1606735606E-03
    n = 12                    sum =  6.4711734220E-03
    n = 13                    sum =  0.0563933694E-03
    n = 14                    sum =  9.9634446704E-03
    n = 15                    sum =  1.2245059910E-02
    n = 16                    sum =  1.4959725739E-02
    n = 17                    sum =  1.0171691191E-02
    n = 10                    sum =  2.1950925504E-02
    n = 19                    sum =  2.6372230275E-02
    n = 20                    sum =  3.1516065002E-02
    n = 21                    sum =  3.7466116007E-02
    n = 22                    sum =  4.4309507663E-02
    n = 23                    sum =  5.2135131336E-02
    n = 24                    sum =  6.1037239396E-02
    n = 25                    sum =  7.1000729600E-02
    n = 26                    sum =  0.2309207650E-02
    n = 27                    sum =  9.5012950503E-02
    n = 20                    sum =  1.0903117067E-01
    n = 29                    sum =  1.2450556479E-01
    n = 30                    sum =  1.4140499035E-01
    n = 31                    sum =  1.6000361764E-01
    n = 32                    sum =  1.0007854160E-01
    n = 33                    sum =  2.0170706709E-01
    n = 34                    sum =  2.2406090133E-01
    n = 35                    sum =  2.4951727072E-01
    n = 30                    sum =  2.7550530157E-01
    n = 37                    sum =  3.0299251132E-01
    n = 30                    sum =  3.3150507057E-01
    n = 39                    sum =  3.6120951770E-01
    n = 40                    sum =  3.9190092512E-01
    n = 41                    sum =  4.2327943102E-01
    n = 42                    sum =  4.5521303039E-01
    n = 43                    sum =  4.8750043603E-01
    n = 44                    sum =  5.1995027700E-01
    n = 45                    sum =  5.5234270194E-01
    n = 46                    sum =  5.9415402091E-01
    n = 47                    sum =  6.1608004921E-01
    n = 40                    sum =  6.4701910010E-01
    n = 49                    sum =  6.7700176013E-01
    n = 50                    sum =  7.0609390403E-01
    n = 51                    sum =  7.3390074540E-01
    n = 52                    sum =  7.6036033250E-01
    n = 53                    sum =  7.8530629015E-01
    n = 54                    sum =  8.0000061539E-01
    n = 55                    sum =  0.3075443529E-01
    n = 56                    sum =  8.5100754527E-01
    n = 57                    sum =  8.6981590019E-01
    n = 50                    sum =  8.0659006930E-01
    n = 59                    sum =  9.0196136777E-01
min K = 234
PO =  3.3017791103E-01
    n = 0                    sum =  3.3017791103E-01
    n = 1                    sum =  5.5371137460E-01
    n = 2                    sum =  7.0420901090E-01
    n = 3                    sum =  0.0511076303E-01
    n = 4                    sum =  0.7225004991E-01
    n = 5                    sum =  9.1672069001E-01
min K = 100
PO =  1.0304105001E-01
    n = 0                    sum =  1.0364105001E-01
    n = 1                    sum =  2.0214150550E-01
    n = 2                    sum =  2.9490529371E-01
    n = 3                    sum =  3.0146503377E-01
    n = 4                    sum =  4.6110779300E-01
    n = 5                    sum =  5.3177593205E-01
    n = 6                    sum =  0.0126274108E-01
    n = 7                    sum =  6.6100521095E-01
    n = 0                    sum =  7.1417124397E-01
    n = 9                    sum =  7.6102539058E-01
    n = 10                    sum =  8.0191220006E-01
    n = 11                    sum =  0.3723041145E-01
    n = 12                    sum =  0.6745503770E-01
    n = 13                    sum =  0.9301005939E-01
    n = 14                    sum =  9.1440231195E-01
min K = 102
PO =  2.0106501591E-05
    n = 0                    sum =  2 0106501591E-05
    n = 1                    sum =  6.5310035056E-05
    n = 2                    sum =  1.1399011247E-04
    n = 3                    sum =  1.7746195344E-04
    n = 4                    sum =  2.5902448201E-04
    n = 5                    sum =  3.6614231055E-04
    n = 6                    sum =  5.0260426457E-04
    n = 7                    sum =  6.7713011921E-04
    n = 0                    sum =  0.9007062793E-04
    n = 9                    sum =  1.1797460530E-03
    n = 10                    sum =  1.5310965239E-03
    n = 11                    sum =  1.9731217301E-03
    n = 12                    sum =  2.5222597241E-03
    n = 13                    sum =  3.2020550091E-03
    n = 14                    sum =  4.0391025037E-03
    n = 15                    sum =  5.0642334911E-03
    n = 16                    sum =  6.3129250149E-03
    n = 17                    sum =  7.0256648147E-03
    n = 10                    sum =  9.0402741113E-03
    n = 19                    sum =  1.1032161599E-02
    n = 20                    sum =  1.4134401521E-02
    n = 21                    sum =  1.7519170601E-02
    n = 22                    sum =  2.1151003099E-02
    n = 23                    sum =  2.5409611741E-02
    n = 24                    sum =  3.0370440559E-02
    n = 25                    sum =  3.8117525900E-02
```

Figure 28.   Computational Results for the proposed Model (OA = 0.90)

```
n = 26                sum =  4.2737470753E-02
n = 27                sum =  5.0319045857E-02
n = 20                sum =  5.0951772142E-02
n = 29                sum =  0.0724002019E-02
n = 30                sum =  7.9721090333E-02
n = 31                sum =  9.2026034373E-02
n = 32                sum =  1.0571020231E-01
n = 33                sum =  1.2083059734E-01
n = 34                sum =  1.3746319319E-01
n = 35                sum =  1.5562206694E-01
n = 36                sum =  1.7533013503E-01
n = 37                sum =  1.9001209300E-01
n = 38                sum =  2.1942713745E-01
n = 39                sum =  2.4374306710E-01
n = 40                sum =  2.8950014732E-01
n = 41                sum =  2.9661069267E-01
n = 42                sum =  3.2196723068E-01
n = 43                sum =  3.5443033121E-01
n = 44                sum =  3.8407575000E-01
n = 45                sum =  4.1010650055E-01
n = 46                sum =  4.4794574667E-01
n = 47                sum =  4.0019430472E-01
n = 40                sum =  5.1264425420E-01
n = 49                sum =  5.4500170299E-01
n = 50                sum =  5.7729220072E-01
n = 51                sum =  6.0906103707E-01
n = 52                sum =  6.4010274642E-01
n = 53                sum =  6.7040533706E-01
n = 54                sum =  0.9978373333E-01
n = 55                sum =  7.2706006514E-01
n = 50                sum =  7.5455303025CE-01
n = 57                sum =  7.8002161221E-01
n = 50                sum =  8.0306314134E-01
n = 59                sum =  0.2611730147E-01
n = 60                sum =  8.4674245700E-01
n = 61                sum =  8.6572131277E-01
n = 62                sum =  8.8305963617E-01
n = 63                sum =  8.9078445520E-01
n = 61                sum =  9.1294102426E-01
min K = 233
PO =  4.0774909057E-02
n = 0                 sum =  4.0774909057E-02
n = 1                 sum =  8.2620567226E-02
n = 2                 sum =  1.2534372005E-01
n = 3                 sum =  1.6073670964E-01
n = 4                 sum =  2.1250070434E-01
n = 5                 sum =  2.5664022300E-01
n = 6                 sum =  3.0070736003E-01
n = 7                 sum =  3.4452507055E-01
n = 0                 sum =  3.8787005561E-01
n = 9                 sum =  4.3052050737E-01
n = 10                sum =  4.7225950906E-01
n = 11                sum =  5.1200674162E-01
n = 12                sum =  5.5221660919E-01
n = 13                sum =  5.9000273606E-01
n = 14                sum =  6.2633911000E-01
n = 15                sum =  6.6006244411E-01
n = 16                sum =  6.9355292691E-01
n = 17                sum =  7.2433493919E-01
n = 10                sum =  7.5315706002E-01
n = 19                sum =  7.7999160093E-01
n = 20                sum =  0.0463369105E-01
n = 21                sum =  0.2763903549E-01
n = 22                sum =  8.4862624417E-01
n = 23                sum =  0.6766676490E-01
n = 24                sum =  0.8409062954E-01
n = 25                sum =  9.0030005102E-01
min K = 200
PO =  4.5914130363E-02
n = 0                 sum =  4.5914130363E-02
n = 1                 sum =  9.3903579410E-02
n = 2                 sum =  1.4364416347E-01
n = 3                 sum =  1.9476654034E-01
n = 4                 sum =  2.4606302216E-01
n = 5                 sum =  2.9950003120E-01
n = 8                 sum =  3.5222469132E-01

n = 7                 sum =  4.0457632090E-01
n = 8                 sum =  4.5610236544E-01
n = 9                 sum =  5.0030705233E-01
n = 10                sum =  5.5190315420E-01
n = 11                sum =  8.0152390695E-01
n = 12                sum =  0.4572748720E-01
n = 13                sum =  0.0730903017E-01
n = 14                sum =  7.2606193071E-01
n = 15                sum =  7.0184097000E-01
n = 10                sum =  7.9450250062E-01
n = 17                sum =  0.2420300170E-01
n = 10                sum =  0.5079449020E-01
n = 19                sum =  8.7441800233E-01
n = 20                sum =  8.9520145181E-01
n = 21                sum =  9.1330300691E-01
min K = 109
  . min K1 = 93
    min K2 = 115
    min K3 = 234
    min K4 = 100
    min K5 = 102
    min K0 = 239
    min K7 = 200
    min K0 = 108
prot_level              S1 S2 S3 S4 S5 S6 S7 S0
-----------             -----------------------
  9.0000000000E-01      1  0  1  1  1  0  1  2
  9.1000000000E-01      1  0  1  1  1  0  1  2
  9.2000000000E-01      1  0  1  1  1  0  1  2
  9.3000000000E-01      1  0  1  1  1  0  1  2
  8.4000000000E-01      1  0  1  1  1  0  1  2
  9.5000000000E-01      1  1  1  2  1  1  1  2
  9.8000000000E-01      1  1  1  2  1  1  2  2
  8.7000000000E-01      1  1  1  2  1  1  2  2
  9.0000000000E-01      1  1  1  2  2  1  2  3

*>>>>  OPTIMAL PROCUREMENT QUANTITY  <<<<*
      Q1 =  6.3245553203E-01
      Q2 =  6.3245553203E-01
      Q3 =  6.3245553203E-01
      Q4 =  8.9442719100E-01
      Q5 =  6.3245553203E-01
      Q6 =  6.3245553203E-01
      Q7 =  1.0954451150E+00
      Q8 =  1.0954451150E+00

          K        S        Q        TOTAL
         ---      ---      ---       -----
   1      93        1        1          95
   2     115        1        1         117
   3     234        1        1         230
   4     100        2        1         103
   5     102        2        1         105
   6     239        1        1         241
   7     200        2        2         204
   8     109        3        2         114
```

Figure 29. Computational Results for the proposed Model (OA = 0.90)

```
PO=  3.5048067631E-01
   n = 0                    sum =  3.5048067631E-01
   n = 1                    sum =  5.0227304772E-01
   n = 2                    sum =  7.3190969232E-01
   n = 3                    sum =  8.3232045021E-01
   n = 4                    sum =  8.9537830320E-01
   n = 5                    sum =  9.3530974000E-01
min K = 93
PO =  1.5811756016E-02
   n = 0                    sum =  1.5811756016E-02
   n = 1                    sum =  3.3964721962E-02
   n = 2                    sum =  5.4500922525E-02
   n = 3                    sum =  7.7504165220E-02
   n = 4                    sum =  1.0320229531E-01
   n = 5                    sum =  1.3156906581E-01
   n = 6                    sum =  1.6240173300E-01
   n = 7                    sum =  1.9581600345E-01
   n = 8                    sum =  2.3173080431E-01
   n = 9                    sum =  2.6972313976E-01
   n = 10                   sum =  3.0963028092E-01
   n = 11                   sum =  3.5113372404E-01
   n = 12                   sum =  3.9306566005E-01
   n = 13                   sum =  4.3741005003E-01
   n = 14                   sum =  4.8135370105E-01
   n = 15                   sum =  5.2521905503E-01
   n = 16                   sum =  5.6855002556E-01
   n = 17                   sum =  6.1092620237E-01
   n = 18                   sum =  6.5190470290E-01
   n = 19                   sum =  6.9111293237E-01
   n = 20                   sum =  7.2821960065E-01
   n = 21                   sum =  7.6295144217E-01
   n = 22                   sum =  7.9509923150E-01
   n = 23                   sum =  8.2452089430E-01
   n = 24                   sum =  8.5114161200E-01
   n = 25                   sum =  8.7495110199E-01
   n = 26                   sum =  8.9599011179E-01
   n = 27                   sum =  9.1430607739E-01
min K = 115
PO =  8.0010479659E-05
   n = 0                    sum =  8.0010479659E-05
   n = 1                    sum =  2.0116900902E-04
   n = 2                    sum =  3.4095319211E-04
   n = 3                    sum =  5.3255059306E-04
   n = 4                    sum =  7.5009599791E-04
   n = 5                    sum =  1.0654743502E-03
   n = 6                    sum =  1.4309510787E-03
   n = 7                    sum =  1.9055336102E-03
   n = 8                    sum =  2.4053453984E-03
   n = 9                    sum =  3.2030333509E-03
   n = 10                   sum =  4.0031725234E-03
   n = 11                   sum =  5.1606735609E-03
   n = 12                   sum =  6.1711734228E-03
   n = 13                   sum =  8.0553933694E-03
   n = 14                   sum =  9.9634146704E-03
   n = 15                   sum =  1.2215059910E-02
   n = 16                   sum =  1.4959725739E-02
   n = 17                   sum =  1.8171691191E-02
   n = 18                   sum =  2.1950025504E-02
   n = 19                   sum =  2.6172299275E-02
   n = 20                   sum =  3.1516065902E-02
   n = 21                   sum =  3.7466116097E-02
   n = 22                   sum =  4.4309507609E-02
   n = 23                   sum =  5.2135131336E-02
   n = 24                   sum =  6.1032239396E-02
   n = 25                   sum =  7.1080729608E-02
   n = 26                   sum =  8.2309207650E-02
   n = 27                   sum =  9.5012950603E-02
   n = 28                   sum =  1.0903117067E-01
   n = 29                   sum =  1.2450556473E-01
   n = 30                   sum =  1.4140499035E-01
   n = 31                   sum =  1.6009361761E-01
   n = 32                   sum =  1.8007054160E-01
   n = 33                   sum =  2.0170706709E-01
   n = 34                   sum =  2.2406090133E-01
   n = 35                   sum =  2.4951727072E-01
   n = 36                   sum =  2.7550530157E-01
   n = 37                   sum =  3.0290254132E-01
   n = 38                   sum =  3.3159507057E-01
   n = 39                   sum =  3.6123151770E-01
   n = 40                   sum =  3.9190025172E-01
   n = 41                   sum =  4.2379131162E-01
   n = 42                   sum =  4.5521393039E-01
   n = 43                   sum =  4.8750013693E-01
   n = 44                   sum =  5.1995627700E-01
   n = 45                   sum =  5.5231279191E-01
   n = 46                   sum =  5.8415407091E-01
   n = 47                   sum =  6.1000094921E-01
   n = 48                   sum =  6.4701918013E-01
   n = 49                   sum =  6.7700176012E-01
   n = 50                   sum =  7.0009330463E-01
   n = 51                   sum =  7.3390074516E-01
   n = 52                   sum =  7.6036033200E-01
   n = 53                   sum =  7.8530629015E-01
   n = 54                   sum =  8.0080061539E-01
   n = 55                   sum =  8.3075143529E-01
   n = 56                   sum =  8.5100754527E-01
   n = 57                   sum =  8.6961590019E-01
   n = 58                   sum =  8.8659006930E-01
   n = 59                   sum =  9.0196130777E-01
   n = 60                   sum =  9.1577955017E-01
min K = 235
PO =  3.3017781103E-01
   n = 0                    sum =  3.3017791103E-01
   n = 1                    sum =  5.5374137460E-01
   n = 2                    sum =  7.0128901030E-01
   n = 3                    sum =  8.0511076303E-01
   n = 4                    sum =  8.7225004991E-01
   n = 5                    sum =  9.1672969001E-01
min K = 100
PO =  1.0364105001E-01
   n = 0                    sum =  1.0304105091E-01
   n = 1                    sum =  2.0714159550E-01
   n = 2                    sum =  2.9190529371E-01
   n = 3                    sum =  3.8116503077E-01
   n = 4                    sum =  4.6140779300E-01
   n = 5                    sum =  5.3177503205E-01
   n = 6                    sum =  6.0126271190E-01
   n = 7                    sum =  6.6100521096E-01
   n = 8                    sum =  7.1417124397E-01
   n = 9                    sum =  7.6102539050E-01
   n = 10                   sum =  8.0191220906E-01
   n = 11                   sum =  8.3722841145E-01
   n = 12                   sum =  8.6715502706E-01
   n = 13                   sum =  8.9304005039E-01
   n = 14                   sum =  9.1410234195E-01
min K = 102
PO =  2.0106501591E-05
   n = 0                    sum =  2.0106501591E-05
   n = 1                    sum =  6.5310035056E-05
   n = 2                    sum =  1.1399041247E-04
   n = 3                    sum =  1.7746196314E-04
   n = 4                    sum =  2.5902416201E-04
   n = 5                    sum =  3.6614234055E-04
   n = 6                    sum =  5.0260425157E-04
   n = 7                    sum =  6.7713011321E-04
   n = 8                    sum =  8.9007562793E-04
   n = 9                    sum =  1.1792150530E-03
   n = 10                   sum =  1.5310985239E-03
   n = 11                   sum =  1.9731247341E-03
   n = 12                   sum =  2.5722597211E-03
   n = 13                   sum =  3.2020550091E-03
   n = 14                   sum =  4.0391025022E-03
   n = 15                   sum =  5.0812331311E-03
   n = 16                   sum =  6.3129250449E-03
   n = 17                   sum =  7.8256491417E-03
   n = 18                   sum =  9.6402741193E-03
   n = 19                   sum =  1.1032161500E-02
   n = 20                   sum =  1.4131101521E-02
   n = 21                   sum =  1.7518170604E-02
   n = 22                   sum =  2.1151809399E-02
   n = 23                   sum =  2.5109641741E-02
   n = 24                   sum =  3.0370440559E-02
```

Figure 30. Computational Results for the proposed Model (OA = 0.91)

```
n = 25          sum =  3.8117525900E-02
n = 26          sum =  4.2737470750E-02
n = 27          sum =  5.0319045057E-02
n = 28          sum =  5.0951721474E-02
n = 29          sum =  8.0724002019E-02
n = 30          sum =  7.9772109033E-02
n = 31          sum =  9.2026034373E-02
n = 32          sum =  1.0571020231E-01
n = 33          sum =  1.2003059734E-01
n = 34          sum =  1.3746349319E-01
n = 35          sum =  1.5562206694E-01
n = 36          sum =  1.7533013503E-01
n = 37          sum =  1.9661209308E-01
n = 38          sum =  2.1942713745E-01
n = 39          sum =  2.4374399710E-01
n = 40          sum =  2.6950014732E-01
n = 41          sum =  2.9561069267E-01
n = 42          sum =  3.2496723060E-01
n = 43          sum =  3.5443933121E-01
n = 44          sum =  3.8407575060E-01
n = 45          sum =  4.1610056055E-01
n = 46          sum =  4.4794571667E-01
n = 47          sum =  4.0019430472E-01
n = 48          sum =  5.1264425420E-01
n = 49          sum =  5.4500179200E-01
n = 50          sum =  5.7772226072E-01
n = 51          sum =  8.0906403707E-01
n = 52          sum =  8.4019274642E-01
n = 53          sum =  8.7010533780E-01
n = 54          sum =  6.9976373333E-01
n = 55          sum =  7.2700006514E-01
n = 56          sum =  7.5455836250E-01
n = 57          sum =  7.8002161221E-01
n = 58          sum =  8.0306314134E-01
n = 59          sum =  8.2611770147E-01
n = 60          sum =  8.4674245700E-01
n = 61          sum =  8.6572131277E-01
n = 62          sum =  8.8305963617E-01
n = 63          sum =  8.9870445520E-01
n = 64          sum =  9.1294102426E-01
min S = 239
PO =  4.0774800057E-02
n = 0           sum =  4.0774800057E-02
n = 1           sum =  8.2920567226E-02
n = 2           sum =  1.2501072005E-01
n = 3           sum =  1.6873570964E-01
n = 4           sum =  2.1250704346E-01
n = 5           sum =  2.5664022300E-01
n = 6           sum =  3.0070736003E-01
n = 7           sum =  3.4452507059E-01
n = 8           sum =  3.8787005501E-01
n = 9           sum =  4.3052050737E-01
n = 10          sum =  4.7225959006E-01
n = 11          sum =  5.1280674162E-01
n = 12          sum =  5.5221066319E-01
n = 13          sum =  5.9000272606E-01
n = 14          sum =  6.2633911090E-01
n = 15          sum =  6.6006744111E-01
n = 16          sum =  6.9355292694E-01
n = 17          sum =  7.2433493319E-01
n = 18          sum =  7.5315709092E-01
n = 19          sum =  7.7999160993E-01
n = 20          sum =  8.0103363105E-01
n = 21          sum =  8.2769993549E-01
n = 22          sum =  8.4862624417E-01
n = 23          sum =  8.6766764190E-01
n = 24          sum =  8.8409862354E-01
n = 25          sum =  9.0030005147E-01
n = 26          sum =  9.1422774071E-01
min K = 201
PO =  4.5914130363E-02
n = 0           sum =  4.5914130363E-02
n = 1           sum =  9.3903579410E-02
n = 2           sum =  1.4364116347E-01
n = 3           sum =  1.9476654094E-01
n = 4           sum =  2.4600302216E-01
n = 5           sum =  2.9950003120E-01
n = 6           sum =  3.5722160313E-01
n = 7           sum =  4.0457032090E-01
n = 8           sum =  4.5010236544E-01
n = 9           sum =  5.0830705233E-01
n = 10          sum =  5.5496345426E-01
n = 11          sum =  6.0152366956E-01
n = 12          sum =  6.4572746720E-01
n = 13          sum =  6.8730909817E-01
n = 14          sum =  7.2606193071E-01
n = 15          sum =  7.6104007090E-01
n = 16          sum =  7.9456250002E-01
n = 17          sum =  8.2420306170E-01
n = 18          sum =  8.5079449026E-01
n = 19          sum =  8.7441006733E-01
n = 20          sum =  8.9520145161E-01
n = 21          sum =  9.1330300694E-01
min K = 109
   min K1 = 93
   min K2 = 115
   min K3 = 235
   min K4 = 100
   min K5 = 102
   min K6 = 239
   min K7 = 201
   min K8 = 109
prot_level          S1 S2 S3 S4 S5 S6 S7 S8
----------          -----------------------
 9.0000000000E-01   1  0  1  1  1  0  1  2
 9.1000000000E-01   1  0  1  1  1  0  1  2
 9.2000000000E-01   1  0  1  1  1  0  1  2
 9.3000000000E-01   1  0  1  1  1  0  1  2
 9.4000000000E-01   1  0  1  1  1  0  1  2
 9.5000000000E-01   1  1  1  2  1  1  1  2
 9.6000000000E-01   1  1  1  2  1  1  2  2
 9.7000000000E-01   1  1  1  2  1  1  2  2
 9.8000000000E-01   1  1  1  2  2  1  2  3

>>>>>  OPTIMAL PROCUREMENT QUANTITY  <<<<<
   Q1 =  6.3245553203E-01
   Q2 =  6.3245553203E-01
   Q3 =  6.3245553203E-01
   Q4 =  8.9442719100E-01
   Q5 =  6.3245553203E-01
   Q6 =  6.3245553203E-01
   Q7 =  1.0954451150E+00
   Q8 =  1.0954451150E+00

        K      S      H      TOTAL
       ---    ---    ---     -----
  1     93     1      1        95
  2    115     1      1       117
  3    235     1      1       237
  4    100     2      1       103
  5    102     2      1       105
  6    239     1      1       241
  7    201     2      2       205
  8    109     3      2       114
```

Figure 31.   Computational Results for the proposed Model (OA = 0.91)

```
PO =  3.5010067603IE-01
   n = 0          sum =  3.5019067603IE-01
   n = 1          sum =  5.0727304772E-01
   n = 2          sum =  7.3100969207E-01
   n = 3          sum =  8.3232045021E-01
   n = 4          sum =  0.8537030326E-01
   n = 5          sum =  9.3530974000E-01
min K = 93
PO =  1.5041756040E-02
   n = 0          sum =  1.5041756010E-02
   n = 1          sum =  3.3064724062E-02
   n = 2          sum =  5.4500922525E-02
   n = 3          sum =  7.7504105229E-02
   n = 4          sum =  1.0328220531E-01
   n = 5          sum =  1.3156906591E-01
   n = 6          sum =  1.6240173300E-01
   n = 7          sum =  1.9591600045E-01
   n = 8          sum =  2.3173000431E-01
   n = 9          sum =  2.6972313976E-01
   n = 10         sum =  3.0963020002E-01
   n = 11         sum =  3.5113372401E-01
   n = 12         sum =  3.9306566005E-01
   n = 13         sum =  4.3741005003E-01
   n = 14         sum =  4.0135370105E-01
   n = 15         sum =  5.2521905503E-01
   n = 16         sum =  5.6055002556E-01
   n = 17         sum =  6.1992620237E-01
   n = 18         sum =  6.5190470730E-01
   n = 19         sum =  6.9111293237E-01
   n = 20         sum =  7.2021960065E-01
   n = 21         sum =  7.6295114217E-01
   n = 22         sum =  7.9591923498E-01
   n = 23         sum =  8.2452009130E-01
   n = 24         sum =  8.5114161700E-01
   n = 25         sum =  8.7495110199E-01
   n = 26         sum =  8.9599341798E-01
   n = 27         sum =  9.1430607739E-01
   n = 28         sum =  9.3025793916E-01
min K = 119
PO =  0.9010479659E-05
   n = 0          sum =  0.9019179659E-05
   n = 1          sum =  2.0146999002E-04
   n = 2          sum =  3.4695312211E-04
   n = 3          sum =  5.3255059091E-04
   n = 4          sum =  7.6009596701E-04
   n = 5          sum =  1.0654743502E-03
   n = 6          sum =  1.4309510787E-03
   n = 7          sum =  1.9055136102E-03
   n = 8          sum =  2.4053459964E-03
   n = 9          sum =  3.2020335099E-03
   n = 10         sum =  4.0031725234E-03
   n = 11         sum =  5.1606735606E-03
   n = 12         sum =  6.4711731220E-03
   n = 13         sum =  8.0563903591E-03
   n = 14         sum =  9.9634416704E-03
   n = 15         sum =  1.2245059910E-02
   n = 16         sum =  1.4959725739E-02
   n = 17         sum =  1.8171691191E-02
   n = 18         sum =  2.1950025504E-02
   n = 19         sum =  2.6372299275E-02
   n = 20         sum =  3.1516065002E-02
   n = 21         sum =  3.7466116007E-02
   n = 22         sum =  4.4309507603E-02
   n = 23         sum =  5.2135131336E-02
   n = 24         sum =  6.1032239106E-02
   n = 25         sum =  7.1000729609E-02
   n = 26         sum =  8.2399207650E-02
   n = 27         sum =  9.5012050603E-02
   n = 28         sum =  1.0903117067E-01
   n = 29         sum =  1.2450558473E-01
   n = 30         sum =  1.4148199035E-01
   n = 31         sum =  1.6003617646E-01
   n = 32         sum =  1.8007054160E-01
   n = 33         sum =  2.0170706703E-01
   n = 34         sum =  2.2486090132E-01
   n = 35         sum =  2.4951727072E-01
   n = 36         sum =  2.7550530157E-01
   n = 37         sum =  3.0290251132E-01
   n = 38         sum =  3.3159567057E-01
   n = 39         sum =  3.6120951776E-01
   n = 40         sum =  3.9190062512E-01
   n = 41         sum =  4.2327943162E-01
   n = 42         sum =  4.5521303039E-01
   n = 43         sum =  4.9750043603E-01
   n = 44         sum =  5.1985627769E-01
   n = 45         sum =  5.5234279191E-01
   n = 46         sum =  5.8415402891E-01
   n = 47         sum =  6.1609001921E-01
   n = 48         sum =  6.4701916010E-01
   n = 49         sum =  6.7700176013E-01
   n = 50         sum =  7.0609390163E-01
   n = 51         sum =  7.3390074546E-01
   n = 52         sum =  7.6030033260E-01
   n = 53         sum =  7.8530029015E-01
   n = 54         sum =  8.0060645390E-01
   n = 55         sum =  8.3075143529E-01
   n = 56         sum =  8.5100754527E-01
   n = 57         sum =  8.6961590019E-01
   n = 58         sum =  8.8659006930E-01
   n = 59         sum =  9.0196130777E-01
   n = 60         sum =  9.1577955017E-01
   n = 61         sum =  9.2011020521E-01
min K = 238
PO =  3.3017791103E-01
   n = 0          sum =  3.3017791103E-01
   n = 1          sum =  5.5374137460E-01
   n = 2          sum =  7.0120901096E-01
   n = 3          sum =  8.0511076303E-01
   n = 4          sum =  8.7225001901E-01
   n = 5          sum =  9.1077969001E-01
   n = 6          sum =  9.4001872545E-01
min K = 101
PO =  1.0364105001E-01
   n = 0          sum =  1.0361105001E-01
   n = 1          sum =  2.0214150559E-01
   n = 2          sum =  2.9190529371E-01
   n = 3          sum =  3.8146503977E-01
   n = 4          sum =  4.6140779380E-01
   n = 5          sum =  5.3177503205E-01
   n = 6          sum =  6.0126274100E-01
   n = 7          sum =  6.6100521006E-01
   n = 8          sum =  7.1171243970E-01
   n = 9          sum =  7.6102539950E-01
   n = 10         sum =  8.0191720006E-01
   n = 11         sum =  8.3723941145E-01
   n = 12         sum =  8.6715502790E-01
   n = 13         sum =  8.9310050303E-01
   n = 14         sum =  9.1140234195E-01
   n = 15         sum =  9.3267430626E-01
min K = 183
PO =  2.0196501591E-05
   n = 0          sum =  2.0196501591E-05
   n = 1          sum =  8.5310035056E-05
   n = 2          sum =  1.1399011247E-04
   n = 3          sum =  1.7746196114E-04
   n = 4          sum =  2.5997446291E-04
   n = 5          sum =  3.6614734055E-04
   n = 6          sum =  5.0250412615E-04
   n = 7          sum =  6.7713011921E-04
   n = 8          sum =  8.9107602793E-04
   n = 9          sum =  1.1702400530E-03
   n = 10         sum =  1.5310905232E-03
   n = 11         sum =  1.9731747391E-03
   n = 12         sum =  2.5222507244E-03
   n = 13         sum =  3.2020550944E-03
   n = 14         sum =  4.0391025032E-03
   n = 15         sum =  5.0912334911E-03
   n = 16         sum =  6.3129250149E-03
   n = 17         sum =  7.8256619117E-03
   n = 18         sum =  9.6402744193E-03
   n = 19         sum =  1.1032161500E-02
   n = 20         sum =  1.4431101571E-02
```

Figure 32.   Computational Results for the proposed Model (OA = 0.92)

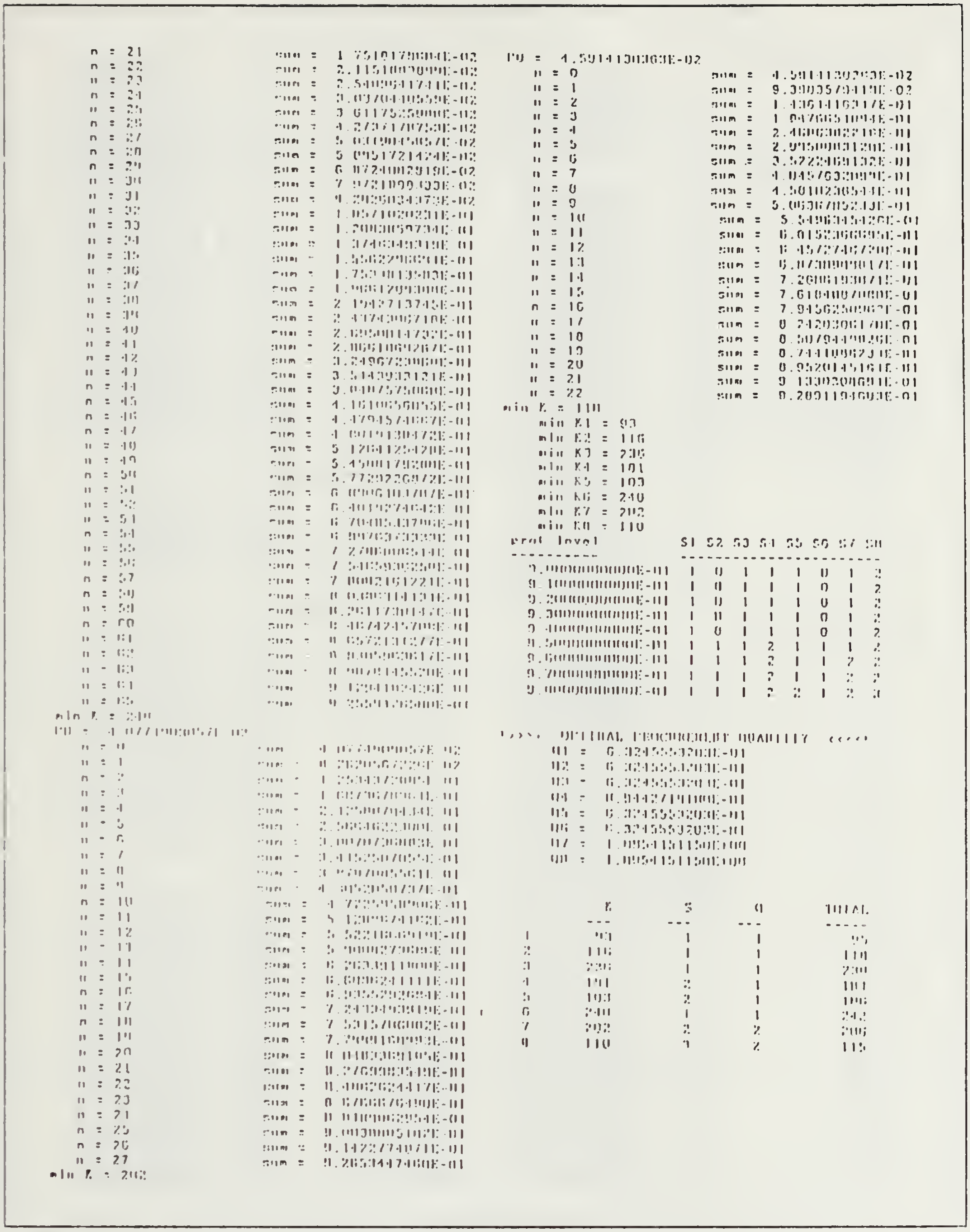

Figure 33. Computational Results for the proposed Model (OA = 0.92)

```
PO=  3.50480067631E-01
   n = 0              sum =  3.50480067631E-01
   n = 1              sum =  5.03273047772E-01
   n = 2              sum =  7.31009688203E-01
   n = 3              sum =  8.32328450216E-01
   n = 4              sum =  8.95379303286E-01
   n = 5              sum =  9.35089740008E-01
min K = 93
PO =  1.59417560496E-02
   n = 0              sum =  1.59417560496E-02
   n = 1              sum =  3.39647249562E-02
   n = 2              sum =  5.45009225725E-02
   n = 3              sum =  7.75041652206E-02
   n = 4              sum =  1.03262295311E-01
   n = 5              sum =  1.31569085501E-01
   n = 6              sum =  1.62491733008E-01
   n = 7              sum =  1.95916000845E-01
   n = 8              sum =  2.31730004131E-01
   n = 9              sum =  2.69723139768E-01
   n = 10             sum =  3.09630200897E-01
   n = 11             sum =  3.51133724404E-01
   n = 12             sum =  3.93065660005E-01
   n = 13             sum =  4.37410050003E-01
   n = 14             sum =  4.81353701085E-01
   n = 15             sum =  5.25719065503E-01
   n = 16             sum =  5.68550025556E-01
   n = 17             sum =  6.10926202037E-01
   n = 18             sum =  6.51904702900E-01
   n = 19             sum =  6.91112932237E-01
   n = 20             sum =  7.28219600065E-01
   n = 21             sum =  7.62951442217E-01
   n = 22             sum =  7.95099234808E-01
   n = 23             sum =  8.24520094008E-01
   n = 24             sum =  8.51141612008E-01
   n = 25             sum =  8.74951101890E-01
   n = 26             sum =  8.95990041179E-01
   n = 27             sum =  9.14336077398E-01
   n = 28             sum =  9.30257939168E-01
min K = 116
PO =  8.00104720658E-05
   n = 0              sum =  8.00104720658E-05
   n = 1              sum =  2.81409999002E-04
   n = 2              sum =  3.46953192111E-04
   n = 3              sum =  5.32550580611E-04
   n = 4              sum =  7.80095967011E-04
   n = 5              sum =  1.06547435028E-03
   n = 6              sum =  1.43095197078E-03
   n = 7              sum =  1.90155336102E-03
   n = 8              sum =  2.10534529864E-03
   n = 9              sum =  3.20203335009E-03
   n = 10             sum =  4.00917252234E-03
   n = 11             sum =  5.16067356006E-03
   n = 12             sum =  6.47117340229E-03
   n = 13             sum =  8.05639030694E-03
   n = 14             sum =  9.96344467040E-03
   n = 15             sum =  1.22745053910E-02
   n = 16             sum =  1.49597257399E-02
   n = 17             sum =  1.81716811131E-02
   n = 18             sum =  2.19500255041E-02
   n = 19             sum =  2.63722992275E-02
   n = 20             sum =  3.15160650022E-02
   n = 21             sum =  3.74861150007E-02
   n = 22             sum =  4.43005076630E-02
   n = 23             sum =  5.21351313306E-02
   n = 24             sum =  6.10322903088E-02
   n = 25             sum =  7.10007290800E-02
   n = 26             sum =  8.23092076500E-02
   n = 27             sum =  9.50129596001E-02
   n = 28             sum =  1.09031170067E-01
   n = 29             sum =  1.24505564073E-01
   n = 30             sum =  1.41404910095E-01
   n = 31             sum =  1.60003617064E-01
   n = 32             sum =  1.80078541100E-01
   n = 33             sum =  2.01707087109E-01
   n = 34             sum =  2.24008901033E-01
   n = 35             sum =  2.49517270072E-01
   n = 36             sum =  2.75505301157E-01
   n = 37             sum =  3.02902541322E-01
   n = 38             sum =  3.31505670057E-01
   n = 39             sum =  3.61209517706E-01
   n = 40             sum =  3.91900825012E-01
   n = 41             sum =  4.23279431062E-01
   n = 42             sum =  4.55213030039E-01
   n = 43             sum =  4.87500136003E-01
   n = 44             sum =  5.19950277600E-01
   n = 45             sum =  5.52311279194E-01
   n = 46             sum =  5.84454020091E-01
   n = 47             sum =  6.16000119021E-01
   n = 48             sum =  6.47019160010E-01
   n = 49             sum =  6.77001786013E-01
   n = 50             sum =  7.06093901083E-01
   n = 51             sum =  7.33900745046E-01
   n = 52             sum =  7.60368332060E-01
   n = 53             sum =  7.85306290015E-01
   n = 54             sum =  8.08606615039E-01
   n = 55             sum =  8.30754435029E-01
   n = 56             sum =  8.51007545027E-01
   n = 57             sum =  8.69615900019E-01
   n = 58             sum =  8.86590069030E-01
   n = 59             sum =  9.01961367077E-01
   n = 60             sum =  9.15779550017E-01
   n = 61             sum =  9.28110205024E-01
   n = 62             sum =  9.39031059066E-01
min K = 237
PO =  3.30177911003E-01
   n = 0              sum =  3.30177911003E-01
   n = 1              sum =  5.53741374060E-01
   n = 2              sum =  7.01209810096E-01
   n = 3              sum =  8.05110703003E-01
   n = 4              sum =  8.72250049091E-01
   n = 5              sum =  9.16729690001E-01
   n = 6              sum =  9.46010725045E-01
min K = 181
PO =  1.03641050001E-01
   n = 0              sum =  1.03641050001E-01
   n = 1              sum =  2.02141505030E-01
   n = 2              sum =  2.91905293071E-01
   n = 3              sum =  3.81165039074E-01
   n = 4              sum =  4.61407793000E-01
   n = 5              sum =  5.31775032005E-01
   n = 6              sum =  6.01262741000E-01
   n = 7              sum =  6.61005210006E-01
   n = 8              sum =  7.14171243097E-01
   n = 9              sum =  7.61125390050E-01
   n = 10             sum =  8.01912200006E-01
   n = 11             sum =  8.37230411045E-01
   n = 12             sum =  8.67455032070E-01
   n = 13             sum =  8.93041005009E-01
   n = 14             sum =  9.14402341095E-01
   n = 15             sum =  9.32267430076E-01
min K = 103
PO =  2.81065015001E-05
   n = 0              sum =  2.81065015001E-05
   n = 1              sum =  8.53100350056E-05
   n = 2              sum =  1.13990412047E-04
   n = 3              sum =  1.77464963044E-04
   n = 4              sum =  2.59024182001E-04
   n = 5              sum =  3.66142340055E-04
   n = 6              sum =  5.02604264057E-04
   n = 7              sum =  6.77110419021E-04
   n = 8              sum =  8.90070827093E-04
   n = 9              sum =  1.17924605030E-03
   n = 10             sum =  1.53109852039E-03
   n = 11             sum =  1.97312473091E-03
   n = 12             sum =  2.52225972044E-03
   n = 13             sum =  3.20205500041E-03
   n = 14             sum =  4.03911250032E-03
   n = 15             sum =  5.06123349011E-03
   n = 16             sum =  6.31292504049E-03
   n = 17             sum =  7.82560491047E-03
   n = 18             sum =  9.64027441093E-03
   n = 19             sum =  1.18321615000E-02
```

Figure 34.   Computational Results for the proposed Model (OA = 0.93)

```
n = 20        sum = 1.4431481521E-02
n = 21        sum = 1.7510170604E-02
n = 22        sum = 2.1151885091E-02
n = 23        sum = 2.5409641741E-02
n = 24        sum = 3.0370441059E-02
n = 25        sum = 3.6117572990E-02
n = 26        sum = 4.2737470753E-02
n = 27        sum = 5.0319045057E-02
n = 28        sum = 5.8951721424E-02
n = 29        sum = 6.0724002018E-02
n = 30        sum = 7.9721099333E-02
n = 31        sum = 9.2026004373E-02
n = 32        sum = 1.0571020231E-01
n = 33        sum = 1.2009359734E-01
n = 34        sum = 1.3746311019E-01
n = 35        sum = 1.5562206991E-01
n = 36        sum = 1.7533813503E-01
n = 37        sum = 1.9661209306E-01
n = 38        sum = 2.1942713745E-01
n = 39        sum = 2.4374306710E-01
n = 40        sum = 2.6950014733E-01
n = 41        sum = 2.9661069267E-01
n = 42        sum = 3.2496723060E-01
n = 43        sum = 3.5443933121E-01
n = 44        sum = 3.8107575080E-01
n = 45        sum = 4.1610569055E-01
n = 46        sum = 4.4794574667E-01
n = 47        sum = 4.9019430472E-01
n = 48        sum = 5.1204425428E-01
n = 49        sum = 5.4500172208E-01
n = 50        sum = 5.7723225072E-01
n = 51        sum = 6.0906403707E-01
n = 52        sum = 6.4019374643E-01
n = 53        sum = 6.7010323707E-01
n = 54        sum = 6.9976373032E-01
n = 55        sum = 7.2706009514E-01
n = 56        sum = 7.5165932250E-01
n = 57        sum = 7.8002101221E-01
n = 58        sum = 8.0396314139E-01
n = 59        sum = 8.2611790147E-01
n = 60        sum = 8.4674245700E-01
n = 61        sum = 8.6572141277E-01
n = 62        sum = 8.8305030170E-01
n = 63        sum = 8.9075441520E-01
n = 64        sum = 9.1294102126E-01
n = 65        sum = 9.2559415500E-01
n = 66        sum = 9.3601790217E-01
min K = 211
P0 = 4.0771000057E-02
n = 0         sum = 4.0771000057E-02
n = 1         sum = 8.7630567236E-02
n = 2         sum = 1.2541137900E-01
n = 3         sum = 1.6472676061E-01
n = 4         sum = 2.1250070131E-01
n = 5         sum = 2.5664032700E-01
n = 6         sum = 3.0070730003E-01
n = 7         sum = 3.4452507055E-01
n = 8         sum = 3.8707005561E-01
n = 9         sum = 4.3052050747E-01
n = 10        sum = 4.7225950906E-01
n = 11        sum = 5.1200674182E-01
n = 12        sum = 5.5221665919E-01
n = 13        sum = 5.9000273036E-01
n = 14        sum = 6.2633911090E-01
n = 15        sum = 6.6006244411E-01
n = 16        sum = 6.9355292604E-01
n = 17        sum = 7.2433121919E-01
n = 18        sum = 7.5315706002E-01
n = 19        sum = 7.7991160993E-01
n = 20        sum = 8.0403303105E-01
n = 21        sum = 8.2760035491E-01
n = 22        sum = 8.4962621417E-01
n = 23        sum = 8.6766764190E-01
n = 24        sum = 8.8409062954E-01
n = 25        sum = 9.0030005102E-01
n = 28        sum = 9.1422774071E-01

n = 27        sum = 9.2653447460E-01
n = 28        sum = 9.3740060510E-01
min K = 203
P0 = 4.5014130363E-02
n = 0         sum = 4.5011130363E-02
n = 1         sum = 9.2903579410E-02
n = 2         sum = 1.4054416347E-01
n = 3         sum = 1.9476054094E-01
n = 4         sum = 2.4006302216E-01
n = 5         sum = 2.9500083120E-01
n = 6         sum = 3.5222169132E-01
n = 7         sum = 4.0457632090E-01
n = 8         sum = 4.5610236541E-01
n = 9         sum = 5.0636705239E-01
n = 10        sum = 5.5196345420E-01
n = 11        sum = 6.0152366695E-01
n = 12        sum = 6.4572746720E-01
n = 13        sum = 6.8739909017E-01
n = 14        sum = 7.2606193071E-01
n = 15        sum = 7.6104007009E-01
n = 16        sum = 7.9156258062E-01
n = 17        sum = 8.2170306178E-01
n = 18        sum = 8.5079449026E-01
n = 19        sum = 8.7441900733E-01
n = 20        sum = 8.9520145164E-01
n = 21        sum = 9.1300709004E-01
n = 22        sum = 9.2091191603E-01
n = 23        sum = 9.4283535590E-01
min K = 111
    min K1 = 93
    min K2 = 116
    min K3 = 237
    min K4 = 101
    min K5 = 103
    min K6 = 241
    min K7 = 203
    min K8 = 111
pref_level           S1 S2 S3 S4 S5 S6 S7 S8
----------           -----------------------
 9.1000000000E-01     1  0  1  1  1  0  1  2
 9.1000000000E-01     1  0  1  1  1  0  1  2
 9.2000000000E-01     1  0  1  1  1  0  1  2
 9.3000000000E-01     1  0  1  1  1  0  1  2
 9.4000000000E-01     1  0  1  1  1  0  1  2
 9.5000000000E-01     1  1  1  2  1  1  1  2
 9.6000000000E-01     1  1  1  2  1  1  2  2
 9.7000000000E-01     1  1  1  2  1  1  2  2
 9.9000000000E-01     1  1  1  2  2  1  2  3

***** OPTIMAL PROCUREMENT QUANTITY *****
   Q1 =  6.3215553203E-01
   Q2 =  6.3215553203E-01
   Q3 =  6.3215553203E-01
   Q4 =  8.9442719100E-01
   Q5 =  6.3215553203E-01
   Q6 =  6.3215553203E-01
   Q7 =  1.0954451150E+00
   Q8 =  1.0954451150E+00

            K        S        D       TOTAL
           ---      ---      ---      -----
   1        93       1        1         95
   2       116       1        1        118
   3       237       1        1        239
   4       101       2        1        104
   5       103       2        1        106
   6       211       1        1        213
   7       203       2        2        207
   8       111       3        2        116
```

Figure 35.   Computational Results for the proposed Model (OA = 0.93)

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